Editor comments

I have now received two very thorough and useful reviews, both of which indicate minor revisions but also list a number of comments that should all be addressed before the paper can be accepted for publication. Both reviewers point to the need to improve the presentation of your article, and the Discussion and Conclusions sections especially.

We worked extensively to make these resolve these important issues and the manuscript is much improved. All changes followed the advice of the reviewers. Of note is a new section requested by Reviewer 2 at the end of the discussion tying back into the continuity equation for ice. The conclusions are now all in paragraph form and follow the highlights suggested by the reviewers. Following reviewer 2's advice we made sure all introductory text is in the intro, all methods text in the methods, etc. The discussion was streamlined and all repeated text was removed. We also improved the legibility of a few figures.

The Supplementary Material also needs improvement, from formatting to style and avoiding repeating figures that are in the main paper.

We removed repeated figures and referenced them now in the main text so it is easy to interface between the main text and the supplementary material. We also removed several figures to reduce the size of the supplementary materials.

I would also encourage you to carefully address reviewer 2 main point 2 on the underlying assumptions of your methods, and make them clear to the readers. I notice that few of the comments in the previous round of reviews have not been addressed and would encourage you to do it now.

We discuss each of these assumptions mentioned by Reviewer 2 in the text in section 4.3. We appreciate the opportunity to clarify our methods.

Thank you for your efforts!

Report #1

Thank you for taking the time to review this manuscript!

Suggestions for revision or reasons for rejection (will be published if the paper is accepted for final publication)

Review the revised version of Anderson et al., TC, September 2020

This is a revised version of a paper that was initially made of 3 parts. Part A and B have been merged into this single manuscript and part C will be re-submitted elsewhere. I do not know how part C will evolve but I applaud the merging of part A and B in a more complete article. I feel that most of my earlier comments were correctly addressed.

At this stage my only major comment is that the paper is lengthy (especially the supplement) so anything that can contribute to make it shorter and easier for the readers will be welcome.

We appreciate the reviewer taking the time to comment on this manuscript. We did everything we could to shorten the manuscript.

Following the suggestions of both reviewers we re-wrote the discussion section on ‘in situ measurements.’ We removed more extraneous discussion points related to backwasting rate with elevation. We removed the repeated mention of the role of measuring ice cliff backwasting at the top of the cliff from the discussion. We have removed all repeated sentences suggested by reviewer 1. We discuss the results in a more systematic fashion and ensure that there are topic sentences for each paragraph. We also removed the sentences from the conclusion that are related to the in situ measurements. We removed repeated text and figures in the supplemental.

General comments.

Maybe this is the result of the merging of two previous manuscripts (not a funny thing to do, I must admit) but I found the article rather long in particular the discussion. See example of repeated statements in my technical comments. Authors should aim at streamlining the article, especially the discussion.

And the conclusion also: A 12 bullet point conclusions is not a nice way to end up the paper. Cannot the authors find 4 or 5 main findings that would be the take home message for the readers, the reasons why they would then cite this study.

We converted the bullet point conclusion into paragraphs as requested and removed extraneous points.

The same applies to the supplement. Make this supplement more concise, better organized so that the reader can navigate through.

We agree with the reviewer and removed the supplementary photos to reduce the content. We now cite individual supplemental figure numbers in the main text to help the reader navigate the additional material. Each supplemental section has a clear heading to indicate what follows that also follows the order in the main text. Each supplemental figure plays a role in supporting the main text now. Much of the original Part A submission is now in the supplementary material. It is necessarily in the supplemental because it was suggested by Reviewer 2 in the first round of reviews.

We changed the section and figure labels following the TC guidelines as well.

Technical comments.

L23 "across our study area, the lower 8 km of the glacier". So that the "study area "is unambiguously defined”.
L25. is it synonymous of the "study area" as defined above? Not clear again.

To resolve these two issues we add a definition of the study area to the abstract.

Original:

“We then use empirical relationships, to estimate melt area-averaged melt across the lower 8 kilometers of the glacier.

Ice cliffs cover 11.7% of the debris-covered tongue, the most of any glacier studied to date, which contribute 26% of melt in study area with a mean debris thickness of only 13.7 cm.”

Changed text:

“We then use empirical relationships to estimate area-averaged melt across the debris-covered tongue (the study area), which constitutes the lower 8-km of the 42-km long glacier.

Ice cliffs cover 11.7% of the debris-covered tongue, the highest percentage from any glacier studied to date. Within the study area, debris cover is relatively thin with a mean thickness of 13.7 cm and the abundant ice cliffs contribute 26% of total melt. ”

L34. The recently published (maybe after the authors submitted?) debris inventory by Herreid & Pellicciotti should be cited I think:
Herreid, S. and Pellicciotti, F.: The state of rock debris covering Earth’s glaciers, Nature Geoscience, doi:10.1038/s41561-020-0615-0, 2020.

Thank you for the suggestion but we don’t think this is absolutely necessary at this point. We have been asked to add a number of citations already to the text.

L48. "compelling" what?

The other other reviewer did not take issue with this word choice so we choose to leave the text as is.

L56 "Glacier"

Corrected ‘glacier’ to ‘Glacier’

L85. "and"

Corrected ‘an’ to ‘and.’

L93. I could count only two questions.

Changed ‘three’ to ‘two’

L147 "the sites where we"

Corrected ‘that’ to ‘where’

The text now:

"Debris measurement locations coincide with the sites where we also measured ice cliff backwasting and sub-debris melt (Fig. 4; Supplemental material)."

L153. delete "a"

Removed the 'a'

L159. "stakes"

changed 'states' to 'stakes'

Figure 6. Is it wise to have the bare ice point of the same color as the curve fitted to the sub-debris measurements? It confused me.

L165. Nonetheless

Corrected. To 'Nonetheless'

L318. "%"

Removed the '%'

L354. Remove first occurrence of "rates"

Corrected from:

"Ice cliffs backwasted at rates similar rates with and without ponds and streams at their base and there is no apparent aspect dependence on backwasting rates (Fig. 7)."

to:

"Ice cliffs backwasted at similar rates with and without ponds and streams at their base and there is no apparent aspect dependence on backwasting rates (Fig. 7) ."

L379. This should be a full sentence.

Original text:

"In total, 11.7 % of the debris-covered tongue of Kennicott glacier is occupied by ice cliffs. See Anderson (2014) for an estimate using an independent method on Kennicott Glacier that is consistent."

Changed to:

“In total, 11.7 % of the debris-covered tongue of Kennicott glacier is occupied by ice cliffs (see Anderson (2014) for an independent and consistent estimate of ice cliff coverage).“

L381. Reference needed here for Changri Nup. Maybe tell that Changri Nup is small (to re-emphasize the added value of your study of examining a large glacier, the largest debris-cover studied so far I think). This comparison to published work could be moved to the discussion by the way.

We added a reference and moved these few sentences into the discussion as requested. The new paragraph reads:

“The 11.7 % ice cliff coverage in the debris-covered tongue (24.2 km^2 in area) of Kennicott Glacier is the highest coverage from any glacier studied to date. The 11.7% coverage is 60% more coverage by percentage than the debris-covered portion of Changri Nup Glacier, the glacier with the second highest ice cliff coverage (Brun et al., 2018; Table 4). The debris-covered portion of Changri Nup Glacier is also substantially smaller in area (1.5 km^2) when compared to the debris-covered tongue of Kennicott Glacier (24.2 km^2). The Kennicott Glacier has the lowest mean debris thickness (13.7 cm) of glaciers with reported ice cliff coverage percentages and supports, by far the highest percentage of ice cliffs. This implies that ice cliff coverage could vary with debris thickness or a variable that co-varies with debris thickness (Table 4).”

L389. "In Figure 11, we"

Corrected as suggested to: “In Figure 11, we”

Also 8+26 = 34% What process is responsible for the remaining 66%? Authors are loosing their readers here (at least me…)

This is a typo and a good catch thank you!

The sentence now reads:

“When averaged across the entire study area, 74% of melt is derived from sub-debris melt and 26 (with extreme bounds of 20 , 40)% from ice cliff melt.”

L392. "26 (20 , 40)%" Unclear notation. What 20 and 40% correspond to. Need to be explained/defined.

The sentence has been amended to explain the bounds. It now reads:

“When averaged across the entire study area, 74% of melt is derived from sub-debris melt and 26 (with extreme bounds of 20 , 40)% from ice cliff melt. “

L397. Do authors mean "below" rather than "above"?

Yes the reviewer is correct. Corrected as suggested:

"The dominance of decreasing sub-debris melt downglacier, due to thickening debris, results in a deviation from the bare-ice melt rate below 700 m a.s.l. (relative to the 2013 glacier surface)."

L434. Help retaining? Help to retain?

This whole section was re-written following the suggestion of the other reviewer so this issue has been resolved.

L460. Before application "to" different glaciers

"to" was added as suggested.

L482. Seems like a repetition of the same statement 2 lines above. Try to be more concise when possible.

Original text:

"Ice cliffs tend to contribute a higher fraction of mass loss as debris thickness increases. This trend is visible on Kennicott Glacier as debris thickens toward the terminus (Fig. 12). This relationship also appears to hold when considering debris-covered glaciers from different regions (Table 4). As debris thickens the contribution of ice cliff melt also tends to increase. This appears to occur even though the fractional coverage of ice cliffs tends to decrease as mean debris thicknesses increase."

New text:

"Ice cliffs tend to contribute a higher fraction of mass loss as debris thickness increases. This trend is visible on Kennicott Glacier as debris thickens toward the terminus (Fig. 12). This relationship also appears to hold when considering debris-covered glaciers from different regions and even though the fractional coverage of ice cliffs also tends to decrease as mean debris thicknesses increase (Table 4)."

L488. Again exact repetition of a statement L484. This lack of concision is a pity, as it makes the readers (reviewer...) nervous.

We removed the repeated line as suggested by the reviewer.

The original paragraph:

"Ice cliffs do not counteract the insulating effects of debris on Kennicott Glacier (Fig. 12). The thin debris within the study area leads to melt rates closer to bare-ice melt rates than most other studied debris-covered glaciers. Measured ice cliff backwasting rates are comparable or higher than measurements from other studies (Table 3). Kennicott Glacier also has the highest fractional coverage of ice cliffs, relative to other studied glaciers, which also serves to increase melt rates (Table 4). Despite this, ice cliffs on Kennicott Glacier do not compensate for the insulating effects of debris. This suggests that the presence of ice cliffs is unlikely to counter the insulating effects of debris on glaciers with thicker debris and/or lower ice cliff coverage."

The new paragraph:

“Ice cliffs do not counteract the insulating effects of debris on Kennicott Glacier (Fig. 12). The thin debris within the study area leads to melt rates closer to bare-ice melt rates than most other studied debris-covered glaciers. Measured ice cliff backwasting rates are comparable or higher than measurements from other studies (Table 3). Kennicott Glacier also has the highest fractional coverage of ice cliffs, relative to other studied glaciers, which also serves to increase melt rates (Table 4). Despite this, ice cliffs on Kennicott Glacier do not compensate for the insulating effects of debris. This suggests that the presence of ice cliffs is unlikely to counter the insulating effects of debris on glaciers with thicker debris and/or lower ice cliff coverage.”

L501. I must say I am not found of this exercise. I do not feel we learn much from it.

We find this exercise to be revealing and vital to the conclusions of this manuscript! It shows how dominant debris is in controlling the mass balance profile on Kennicott Glacier. This is essentially a sensitivity test and we think an important contribution to the field . The other reviewer also had no issue with this line of reasoning. We do not make a change here.

The other reviewer said this about this section: “Convincing hypothesis tests above.”

L503. This is as reduction factor of 10 or a multiplicative factor of 0.1

Removed “(a 10-fold reduction)” to remove ambiguity.

L519. useful sentence???

This sentence and paragraph was removed and replaced with new text.

Conclusion. Again lack of concision. The conclusion should extract the main message and not a list of 12 bullet points… For me the main message is that for the largest debris-covered glaciers studied so far, despite a very high density of ice cliffs compared to others studied glaciers, their contribution to the tongue-wide ablation is moderate. To be a bit provocative, maybe our community should spend more energy estimating spatial pattern of debris thickness than ice cliffs density.

We re-formated the conclusions following your suggestion. They are now in paragraph form. We also removed the conclusions related to details of the in situ measurements. We also incorporated your suggestion of the main message. Based on conversations with other researchers, they are interested in other conclusions as well so we also include other items here.

L535. "near the terminus near the margin" strange formulation.

This is simply a typo which has been corrected.

L568. Is not "vital" a bit strong???

This word choice seems rather justified from the rest of the analysis above, as well as the extensive sensitivity analysis in the supplemental materials. By process of elimination ice dynamics are necessary here. The other reviewer had no issue with this word choice, either. The conclusion was re-written without this word.

We add a new paragraph above the conclusion that makes this more clear.

Supplement.
Authors should use the same font throughout the text of the supplement, organize the different sections clearly for easier navigation, e.g., increase a bit the line spacing also.

The text, not associated with section titles is now all the same font. We increase the spacing between sections though.

Not providing a line-numbered supplement seriously complicated the life of referee who was almost exhausted when he started to review this part of the article…

Sorry for this. Just didn't cross our minds. We will do this for future submissions, though.

Reducing the size of the supplement file (55 Mo) should be possible without loosing readibility.

The size was reduced and is now within TC guidelines (less than 50 MB).

Fig S3. Dead ice portion. Above or below 5 cm/day? For me dead ice is almost stagnant.

Good point. This is the error associated with the method from the citation in the caption. Because Armstrong et al. (2016) used this definition we choose not to deviate here from that definition already published.

Fig S4 "repeated measurements"

Good catch.

"Error bars in measured debris represent changes in debris thickness measurements upon repeated measurement."

changed to:

"Error bars for debris thickness represent changes upon repeated measurement."

Fig S5. Why not showing directly the difference instead of two set of points?

While this could be better there are already a ton of plots and we feel that this plot is just as good at showing how this correction does not effect the overall results of the study. Ultimately this seems like more work than the potential payoff for readers.

Fig S6. It is not clear how the others studies were selected. I think it would be very useful to add the data from a previous compilation made by Kraaijenbrink et al. in their Supplementary Figure S5. Your compilation would gain exhaustivity.

Kraaijenbrink, P. D. A., Bierkens, M. F. P., Lutz, A. F. and Immerzeel, W. W.: Impact of a global temperature rise of 1.5 degrees Celsius on Asia’s glaciers, Nature, 549(7671), 257–260, 2017.

As in the caption: the point here is to only show data from debris-covered glaciers at a **similar latitude** to the Kennicott Glacier. The plot only includes data from glaciers are similar latitudes and these were all of the data we could find. Including more glaciers will detract from the point of the plot. That is not to take away from the Kraaijenbrink compilation at all just not our intent with this plot.

I do not see the point of having some figures repeated both in the main and in the supplement (Fig 16 and 17 at least).

We removed these figures.

Fig S17-S35. Cannot these sensitivity tests be summarized in one or two paragraphs? Do the authors really need to show all figures?

We do this on purpose so the reader can see the effect of each of these changes in the supplementary material. The main text has such a summary. We do not want to repeat that here. The first round of review seemed to also miss our description of uncertainty so we also wanted to make it clear the effect of each of these changes. For these reasons the figures are included. We also do not understand the issue with having a longer supplementary section. There is simply just more evidence to support the main conclusions in the text, so we leave the content in but work on the organization of the supplemental material.

Report #2

Thank you for taking the time to review this manuscript!

Review of ‘Debris cover and the thinning of Kennicott Glacier, Alaska: in situ measurements, automated ice cliff delineation and distributed melt estimates’ by Anderson et al, submitted to The Cryosphere

The revised manuscript by Anderson et al has combined parts A and B to focus on distributed melt estimates for most of the debris-covered area of Kennicott Glacier, Alaska. The scope is much clearer and the study is greatly improved in this formulation, which I appreciate has been a major undertaking for the authors. The presentation and analysis of observations from debris covered glaciers in Alaska are a welcome contribution to The Cryosphere, and this study uses empirical models to complement the remote sensing observations and inferences of Brun et al (2018) regarding the importance of ice cliffs and sub-debris melt, and the resulting patterns of glacier-wide melt rates.

At this point I have few substantive comments, although I think the study would benefit aesthetically from additional careful editing and textual revision. In particular, some content seems misplaced between Methods/Results/Discussion,

We have addressed this issue by following all the comments of this reviewer. We moved one paragraph into the introduction and melded another into the discussion. See below detailed comments for the specifics.

and the storyline is not entirely clear for the discussion,which comes up just short of stating explicitly that since melt rates are not the key factor driving the zone of maximum thinning, reduced ice fluxes must play an important role.

We have streamlined the discussion by removing several more minor points, especially in the ice cliff backwasting section. We replaced Section 4.4 with one that walks the reader through our conclusion that the reduction of ice flow from upglacier is necessary for explaining the location of the ZMT.

My comments below are extensive, but primarily relate to the presentation of the study. There are a few more substantive comments, but none that require additional analysis.

Summary comments:

1. A need for careful final editing in terms of grammar and accuracy. At present the writing style is not particularly satisfying to read: many sentences start with 'it,' 'but,' 'and,' 'because,' etc that should be linked to the preceding thought, and the editing/proofreading has not been thorough.

We combined these sentences following the reviewer's advice.

2. When uncertainty values are given, it is not clear how they were derived or what they correspond to.

We have clarified this in each location requested by the reviewer. We also removed any repeated mention of the in situ uncertainty values.

In terms of representativeness, the authors seem to make some key unstated assumptions: 1) that the peak ablation season is a good proxy for annual-average ablation rates (possibly not true for ice cliffs), 2) small-scale debris thickness variability is not important to assess glacier-scale melt rates despite the nonlinear relationship between debris thickness and melt).

Although I disagree with both of these assumptions, I do not think they affect the conclusions of the study. I do, however, think those assumptions should be made clear; this study makes good use of empirical methods to ask an important theoretical question, but the reader needs to be reminded of the fundamental assumptions of the framework of analysis.

Here the two reviewers clash. One would like a simpler, more fluid read, while the other prefers more details. This is one reason why supplemental is large. It allows readability of the main draft while also providing the detailed support the reviewers desire.

There are valid arguments why the assumptions laid out here by this reviewer do not matter for the conclusions of this paper. The reviewer even states that these assumptions are unlikely to affect our conclusions. We mention these assumptions now in the lower part of the discussion but also point to a new section in the supplemental that further discusses them to increase readability as per the desires of reviewer 2.

For the small-scale variability we now include this sentence in Section 4.3.1:

"Our distributed melt-estimation approach assumes that small-scale debris thickness variability has a negligible effect on area-averaged melt rates, despite the non-linear debris-melt rate relationship. The sensitivity test in this paragraph reveals how improbable it is for small-scale debris variability to lead to maximum melt rates in the *ZMT* (see Section S1.7 for further discussion)."

We now include this paragraph in the Supplemental material for the small-scale variability assumption (note that we follow the logic of the reviewer here in the text we include):

"Our approach assumes that small-scale debris thickness variability has a negligible effect on area-averaged melt rates, despite the non-linear debris-melt rate relationship. Including small-scale variability in debris thickness cannot decrease the *effective* debris thickness (therefore increasing local melt) below the minimum in situ measured debris thickness in any given elevation band. We see from Figure 5 that the minimum measured debris thicknesses are much larger in the *ZMT* than immediately above the *ZMT*. Small-scale variability in debris thickness therefore cannot to lead to a peak in melt rates in the *ZMT*. It is also highly likely that the range of plausible effects from small-scale debris variability lie within extreme sensitivity tests as described in this and Sections 4.4, and S3.1, further suggesting that our assumption is unlikely to affect our conclusions."

For the ice cliff assumption we now include this paragraph in section 4.3.1:

"We implicitly assume that the peak melt season (the June to August study period) is a good proxy for annual-average ablation rates, though it is exceedingly unlikely that this assumption affects our conclusions. During shoulder seasons ice cliffs tend to produce high *relative* melt, even though *absolute* melt must decrease due to the decline in available energy. In order for *absolute* annual area-averaged ablation rates to be maximized in the *ZMT*, ice cliff backwasting rates in shoulder seasons would need to be more than 6.5 times those measured in the summer of 201, due to reduced sub-debris melt, and last for the same duration as the June to August study period."

3. Some content related to the continuity equation in the introduction and methods, but then this isn't really discussed in the results and discussion at the end. I guess these parts of the analysis have been retained for later publication, but it feels like an unfinished thought here; perhaps not entirely necessary (yet) or a bit of discussion would close the gap to simply indicate clearly that based on this analysis it should be tested whether a reduced ice flux can explain the ZMT.

This is a good point. We remedy this by adding a section at the end of the discussion to tie the continuity equation back in and explain our logic better.

Comments:
L18. 'melt reducing' is a compound modified and should normally be hyphenated

Corrected here and throughout the manuscript.

L19. This sentence is a bit complex due to the frequent commas. There should not be a comma after 'thinning'. The 'but' is counterintuitive here and is better replaced with 'and' as Kennicott is an example of the dynamics represented above. However, the 'under insulating debris cover' is only demonstrated by your manuscript later on (it is not yet background knowledge that the debris is thick), so perhaps best to remove 'insulating'.

The abstract was re-written.

L22. Although an excellent contribution, this is a semi-automated method as it requires training data.

We appreciate the reviewers opinion on the the definition of 'automated' but we disagree. This is the first application of this method such that the parameters need to be estimated and the results validated against digitized ice cliffs. Further application of the ABT method to other can use those same parameters and apply the method to other glaciers. So it is not clear how the reviewer can assert that '**training data is required.**' From our view that is a presumptuous statement about the method we develop here. For these reasons and the fact that the other reviewer does not have an issue with our use of the term 'automated' we choose to make no change.

L23. Why the comma after 'relationships'?

Corrected.

L25. 'which' should be 'and' for the sentence to make sense grammatically: Ice cliffs cover 11.7% of the debris-covered tongue [, ... ,] and contribute...' L26. 'with a' should be 'which has'. As written, the literal meaning is that the ice cliffs have a mean debris thickness of 13.7cm, but I suppose that this should refer to the debris-covered area.

Corrected.

The sentence was split into three and now reads:

"Ice cliffs cover 11.7% of the debris-covered tongue, the most of any glacier studied to date. Within the study area, debris cover is relatively thin with a mean thickness of 13.7 cm. The abundant ice cliffs contribute 26% of melt in study area."

L29-30. This is the first time that the decline in ice discharge is mentioned in the abstract. Introducing at the end of current line 24 with a succinct methodological description would clarify to readers where this comes from. Otherwise, the abstract should also have a line along the lines of 'We find a decline in ice discharge from up-glacier...'

For us it doesn't make too much sense to put a description up higher. An easier fix for this issue is to add a bit more text to L29 which explains the logic.

"We therefore suggest that the decline in ice discharge from upglacier is the vital control defining the zone of maximum thinning."

changed to:

"By process of elimination from the continuity equation for ice we therefore suggest that the decline in ice discharge from upglacier is a necessary control on the location of the zone of maximum thinning."

L37. The debris is not itself expanding, but the debris-covered areas are.

Changed from:
"Adding to this insulating effect, debris is expanding for many glaciers even as they contract in response to climate warming (e.g., Tielidze et al., 2020). "

to:

"Adding to this insulating effect, debris covers are expanding for many glaciers even as they contract in response to climate warming (e.g., Tielidze et al., 2020). "

L38-39. I suggest joining these sentences as they are directly linked theses. It's rarely a good idea to start a sentence with 'But'. The first clause, however, is a hypothesis that should have a reference. In addition, the only study I know of that has assessed whether debris is actually thickening rather than simply expanding in coverage is (Gibson et al., 2017).

We correct all of these issues:

"Expanding and thickening debris cover should reduce glacier thinning relative to glaciers without debris. But the melt-suppressing effect of debris is not always apparent the observed thinning patterns of glaciers even when debris is thick and debris coverage is extensive (e.g., Kääb et al., 2012; Gardelle et al., 2013)."

changed to:

Expanding and thickening debris cover should reduce glacier thinning relative to glaciers without debris (Banerjee, 2017; Gibson et al., 2017), but the melt-suppressing effect of debris is not always apparent the observed thinning patterns of glaciers even when debris is thick and debris coverage is extensive (e.g., Kääb et al., 2012; Gardelle et al., 2013).

L41. (F. Brun et al., 2019) is a better reference for this phenomena, although the 2018 study is also appropriate.

We think the "e.g.," already in the text takes care of this comment. No change made.

L43. Again, I suggest linking this sentence to the one before: ', and has been documented...' Also, Asia has already been mentioned just two sentences before, so this could be 'and has also been documented in Europe'.

We follow the suggestion from the reviewer.

"This apparent paradox, in which rapid thinning is occurring under insulating debris cover is known as the 'debris-cover anomaly' (Pellicciotti et al., 2015). It has been documented in both Asia and in the European Alps (Nuimura et al., 2012; Agarwal et al., 2017; Lamsal et al., 2017; Wu et al., 2018; Mölg et al., 2019)."

original changed to:

"This apparent paradox, in which rapid thinning is occurring under insulating debris cover is known as the 'debris-cover anomaly' (Pellicciotti et al., 2015) and has also been documented in the European Alps (Mölg et al., 2019). "

L46. This phenomena being global or not is a bit out of scope for this paper. It's an interesting supposition but the important aspect for the background of your study is that it also occurs in Alaska.

A small change to the wording can address this comment, while also honoring our intentions here.

Changed from:

"The 'debris-cover anomaly' may in fact be a global phenomena."

to

"The 'debris-cover anomaly' is occurring in Alaska, suggesting that it may be a global phenomena."

L47. No need for 'from' in 'from within'

Corrected.

L48. ‘Compelling’ is out of place or a word is missing: ‘This is a compelling ___ because ...’

Removed ‘a’ to fix this issue.

Edited sentence:

“This is compelling because the Wrangell Mountains are in Alaska and at a latitude (61 to 62 deg. N) where the effects of debris on glacier mass balance has received almost no attention.”

L54-55. I suppose that this question is the overarching drive of this analysis, and should be highlighted as such rather than as a rhetorical question in the text.

We follow the suggestion of the reviewer:

“Why does the maximum thinning of Kennicott Glacier occur under debris at rates similar to nearby debris-free glaciers?”

changed to:

“This brings us to our overarching question: *Why does the maximum thinning of Kennicott Glacier occur under debris at rates similar to nearby debris-free glaciers?”*

Eq 1. The equation requires units for each of the quantities to be the same (m/a or m w.e./a) which should be noted somewhere, since b* usually differs in units from dH/dt and the flux divergence.

This equation is used for the introduction formally laying out that both mass balance and ice dynamics matter for glacier thinning. The inclusion of units here just complicates the introduction and ties in units where they are not relevant. Lower down we highlight that all melt is in ice equivalent units.

Also, the flux divergence terms are not strictly correct, they should be dQ_x/dx and dQ_y/dy and are partial derivatives.

We have edited the equation to reflect this suggestion:

$$\frac{dH}{dt} = \dot{b} - \frac{\partial Q_x}{\partial x} - \frac{\partial Q_y}{\partial y}$$

L61-75. It would be good to include a reference for the continuity equation and its simplified version here; this has been done before and deserves a reference. Cuffey and Paterson is the obvious choice because it contains all these concepts, but the continuity equation has been applied to mountain glaciers extensively in Peru and the Alps since the 1990’s, and since the 1970’s at least for the ice sheets. I’m not suggesting a comprehensive list, but a reference or two would be value-added.

From our view, the continuity equation is the result of applying mass conservation to the transport of a 'fluid.' The equation has been used since the development of fluid mechanics and by the first contributors to quantitative glaciology. For this reason we find the the Cuffey and Paterson reference is enough here because it is the state-of-the-art glaciology text that already honors that historical perspective. For this reason we do not make any change here.

L72. Benn et al (2017) is one of the few studies that have tried to estimate b*_e, and is highly relevant.

Add the reference at the end of the sentence.

L76. This is a nice way to present the various hypotheses.

Thank you, we appreciate it!

L80. I believe you intended to italicize the 'M' in 'Melt' as well.

Corrected.

L84. The comma should be removed from this statement.

Comma removed.

L85. This is not necessarily upglacier of the debris, but upglacier of the thick debris.

The suggestion from the reviewer over complicates what we intend to stay here. By adding too many details this sentence will become too complex and take away from the point we are making. Whether thin debris enhances melt in a fashion actually important for this process is up for debate (see Fyffe, et al., 2020). The first reviewer also did not take issue with this wording. We leave this sentence as it is for these reasons.

Typo: 'thinning and reduced ice flow'

Corrected by adding a 'd.'

L87. (Fanny Brun et al., 2018) summarized this concept very well in their Figure 11.

L89. Typo: 'revealing'

Corrected from 'reveling' to 'revealing.'

L90. It's definitely marginally acceptable to reference your own thesis for a paper on the same topic.

My thesis is actually pretty different than the work presented here. Considering the history of activity on Kennicott Glacier we would like to point to it so readers will find an additional resource. Because the other reviewer did not have an issue here, and we do not share the intuition of the review, we prefer to leave the reference in. This reference also cited again below.

L92. ‘from across Kennicott Glacier’ is already clear from this sentence

Removed. The sentence now reads:

“If melt hotspots are the sole control on the *location and magnitude* of the zone of maximum thinning or *ZMT* for Kennicott Glacier then we should expect melt rates (averaged across the glacier width) to be maximized there.”

L93-95. The mention of 2011 appears from nowhere since it hasn’t been introduced that this is the period you have data for. Perhaps it is tidier to leave the questions unconstrained temporally, but then in the next paragraph to introduce the summer of 2011 as the period of observations.

Good catch. We removed 2011 from these questions. The following paragraph now reads:

“To address these questions, we quantify the role of ice cliffs and sub-debris melt across the debris-covered tongue of Kennicott Glacier during the summer of 2011. We limit our scope to ice cliffs and sub-debris melt, leaving an examination of surface ponds and streams as later contributions. Our analysis is rooted in abundant in situ data collected from the glacier surface in the summer of 2011. We measured debris thickness, sub-debris melt rates, and ice cliff backwasting rates. In addition to helping address the questions raised above, these in situ measurements, from this latitude and Alaska, are vital for developing a global perspective on glacier response to climate change as well as the next generation of global glacier models incorporating the effects of debris cover.”

You then still need to be careful to indicate that the same patterns are expected to be apparent in the summer of 2011 as for long term/annual mass balance and thinning, for example based on Das et al (2014) and possibly the ITS_LIVE velocities?

Indeed, we addressed this in the last set of revisions, so there is no need for a correction here.

Lower in section 4.3.1 you will find:

“For this discussion we make the assumption that the *ZMT* – which was stable between the 1957 to 2004 and 2000 to 2007 time periods-- remained in the same location during summer of 2011.”

L98-99. I think it’s fine to relegate the analysis of streams and ponds to another paper, but if these are also potential contributors to surface mass balance, doesn’t this cut your thesis short? I.e. you are no longer able to make a statement for all melt hotspots combined, but only for cliffs. Now, we certainly know that there are few ponds on Kennicott, and their location is different to the TMZ; why not simply pretend they melt at the same rate as cliffs (somewhat as in (Kraaijenbrink, Bierkens, Lutz, & Immerzeel, 2017)) so that your ablation budget is complete? Streams are even more problematic, since they are prevalent and unconstrained. I make this point not to criticize your work; I am convinced that the hotspots are only part of the explanation and that ice dynamics are vital to explain the debris cover anomaly. I just this your huge amount of work here will be much stronger by representing these somehow (even as a hypothesis test).

Thank you for this suggestion. It is helpful. We include a hypothesis test at the end of the discussion that follows:

"While we do not explicitly document the melt rate of ponds and streams (i.e., melt hotspots) we follow Kraaijenbrink et al. (2017)'s approach and assume they melt at the same rate as ice cliffs. Using this logic, in order for ice cliffs (melt hotspots) in the *ZMT* to compensate for the insulating effects of debris, ice cliff (melt hotspot) area would need to increase from 11.7% to 90% of the glacier surface. Ice cliffs, ponds, and streams assuredly do not occupy 90% of the *ZMT*. This again suggests that ice cliff and other melt hotspots do not control the location of the *ZMT*."

L105. I believe this should be WorldView-1.

Corrected:

"We therefore present and apply a new method for remotely delineating ice cliffs using high-resolution WorldView-1 orthoimages."

L117. Is this 20% figure from your own digitization (if so, of what imagery and when?), or from (Scherler, Wulf, & Gorelick, 2018)? Just best to indicate the source (or 'approximately'), as these numbers often get recycled.

We follow this suggestion.

"As of 2015, 20% of Kennicott Glacier was debris-covered."

Changed to

"As of 2015, approximately 20% of Kennicott Glacier was debris-covered."

L130. There is an extra space before 'duration'.

Space removed.

Understanding that the scope of this study is the bulk of the ablation season for this glacier, have you considered the representativeness of this period to the full-year ablation budget? This is not likely to change your outcomes, but it is worth thinking whether ablation hotspots such as cliffs and ponds 'turn off' their melt contributions at the same time as the general debris-covered tongue. This probably depends based on the glacier- specific site and characteristics, but cliffs and ponds could have positive surface energy balanceduring periods of the year when conduction through debris is already negligible. The assumption here (with regards to the research question) is that the peak ablation season corresponds well to the average annual ablation across the glacier. I don't think this assumption is particularly bad, but it should be made explicit.

Absolutely this is certainly true but we agree with the reviewer that this effect plays a minor role. As described above we chose to add a few sentences about this in the discussion section. Because it is minor we do not mention it until the discussion section.

L136-142. I completely agree with all of this content, but it belongs in the Introduction.

These lines were moved up to the introduction as suggested.

L147. Perhaps combine this sentence with L148-149 'by digging through...'?

Corrected to:

"We measured debris thicknesses at 109 sites by digging through the debris to the ice surface (after Zhang et al., 2011). Debris measurement locations coincide with the sites where we also measured ice cliff backwasting and sub-debris melt (Fig. 4; Supplemental material). "

L152. It is not clear what these values correspond to – the uncertainty and variability of the measurements themselves, or (as it appears in Fig 5) of the altitudinal curve-fit. For each of these, a bit of additional information is needed. How did you get an thickness uncertainty of 0.3cm? This is incredibly precise considering the challenge of the measurement – excavation to the ice surface without disturbing the ice surface, finding the reference height, ensuring a vertical measurement, etc. For a 30cm pit, this implies a measurement within 6 degrees of vertical, ignoring all other uncertainties, or for 60cm, 4 degrees. What does the standard deviation correspond to – the variation between measurements at the same elevation? I guess that the 'maximum error' is the maximum standard error of the elevation's mean debris thickness?

In order to clear up any confusion we expand the explanation of errors. We just simply re-measured the debris thickness at 52 sites. We do not want to over complicate the text as well. The original text was:

"The mean uncertainty of the debris thickness measurements is ±0.3 cm, with a standard deviation of ±1.8 cm, and a maximum error of ±6.7 cm (Fig. 5). Error estimates were based on repeated measurements, but measurement error is a negligible compared to the changes in debris thickness down and across the glacier."

and was changed to:

"Based on repeated measurement of debris thickness at 52 sites (with a mean debris thickness of 7.9 cm), the mean uncertainty of the debris thickness measurements is ±1.3cm, the standard deviation is ±1.4 cm, and the maximum error measured within the population of re-measured sites is ±6.7 cm (Fig. 5; Fig. S4). We consider measurement error to be negligible compared to the changes in debris thickness down and across the glacier."

L159. Again, the 'how' of the uncertainty is as important as the value. In this case I would suspect that this uncertainty represents the uncertainty in the stake height measurements, spread over time?

We have changed the original text:

"The mean uncertainty in the sub-debris melt rates was ± 0.1 cm d^{-1}, the standard deviation was 0.05 cm d^{-1}, and the maximum error was 0.25 cm d^{-1} for the three ablation states with the shortest measurement period of 8 days. These measurement uncertainties are small compared to the changes in melt rate with debris thickness (Fig. 6)."

to:

"We estimated uncertainty by assuming a combined ±2 cm uncertainty in the marking of the ice surface on each ablation stake and the measurement between marks. We include all stakes as they vary in space and time. We measured the tilt of each ablation stake at the end of the measurement period which averaged 5° from vertical. The mean uncertainty in the sub-debris melt rates is ±0.06 cm d^{-1}, the standard deviation is 0.03 cm d^{-1}, and the maximum error is 0.125 cm d^{-1} for the three ablation stakes with the shortest measurement period (8 days). These measurement uncertainties are negligible compared to the changes in melt rate with debris thickness (Fig. 6)."

Similarly for L176.

This information was in the supplemental figure referenced in the sentence but it should be brought into the main text. We bring it into the updated sentence now:

"The mean error of the ice cliff backwasting rates is ±0.5 cm d^{-1} (Fig. 7; Fig. S9). Maximum error is ±1 cm d^{-1} for 10 cliffs that were measured over the shortest interval (21 days). The standard deviation of errors is ±0.2 cm d^{-1}."

Changed to:

"The mean error of the ice cliff backwasting rates is ±0.5 cm d^{-1} based on an estimated measurement uncertainty of ±20 cm applied to both the initial and final distance measurement (Fig. 7; Fig. S9). Maximum estimated error is ±1 cm d^{-1} for 10 cliffs that were measured over the shortest interval (21 days). The standard deviation of errors is ±0.2 cm d^{-1} based on error estimates from all 60 ice cliffs."

L165. Typo in 'nonetheless'

corrected to 'nonetheless'

L166-171. This is nice content and a very tidy synthesis of key points from past work on cliffs, but shouldn't this be in the Introduction? No methods appear until L171-2

We could not find a natural way to incorporate this into the introduction so we moved the content of these sentences to the discussion where they directly relate to the arguments we make. So we effectively follow the reviewer's suggestion.

L196-197. The content of the stereoimagery is out of place here, and interrupts the description of the ice cliff mapping method, for which it seems irrelevant. Perhaps it could be part of 2.3, since you use the elevation to prescribe the melt rates across the glacier?

Good catch. We moved this content into the introduction of the methods. Which now reads as:

"Our methods fit into three broad categories: 1) in situ measurements; 2) automatic ice cliff delineation; and 3) distributed melt rate estimates. In situ measurements were made within the broad study area shown in Figure 1C, which is within 8 kilometers of glacier terminus. Distributed melt estimates on the other hand are made across the delineated medial moraines shown in Figure 4A. In total the distributed melt estimates were made over 24.2 km^2 which we consider here to be the 'debris-covered tongue' of the glacier. In situ measurements were all made within the full field campaign duration and study period from 18 June to 16 August 2011. We correct each measured melt rate to represent the full duration of the study period, as described below. We used WV stereoimagery from 2013 to produce glacier surface DEMs at 5 m spatial resolution using the Ames Stereo Pipeline (Shean et al., 2016), which we use to represent the glacier surface during the study period."

L222. As written, I'm not sure which problems are for 'ABT and SED' or 'SED only'. This becomes clearer later in the paragraph, so maybe simplify and remove the indication of which method suffers from which problems here?

We clarified this by making sure it is clear which problems are linked to which method:

"The last step in our processing process is morphological filtering to remove spurious data. Both delineation methods (*ABT* and *SED*) produce false positives from shaded, over-exposed, or textureless debris cover (*SED* only). The *SED* approach produces many false positives, which generally have a characteristic speckled appearance, and often occur in small, isolated groups. We apply morphological opening (Dougherty, 1992) to remove these isolated false positives in both the *ABT* and *SED* approaches (skimage.morphology.opening; Fig. 8). In addition, the *SED* approach creates false positives in regions that have been over-exposed by the saturation stretch and therefore lack texture. For the *SED* method only, we remove these false positives by masking pixels with the maximum brightness."

We felt that removing the labels for the different methods would actually do the opposite of what the reviewer intends so we clarified the issue in another fashion.

L231-2. Makes sense to reference (Steiner, Buri, Miles, Ragettli, & Pellicciotti, 2019) here. This difference is 3% of total cliff area or 3% area mismatch (non-overlapping areas)? Please make it clear in the text.

We note now that the total ice cliff area differs by 3 %. Changed from:

"As these independent delineations agreed within 3% in their ice cliff area, we consider operator misidentification to be a negligible source of error."

to

"As these independent delineations agreed within 3% in their total ice cliff area, we consider operator misidentification to be a negligible source of error."

L259-270. I am impressed by the effort to represent the debris thickness variability based on flow units, which is a key aspect of spatial heterogeneity in deriving glacier-wide melt estimates based on (necessarily) spatially-biased measurements.

Thank you for recognizing that!

L274. It's nice to see h* explained in very clear terms (the half-melt thickness) and related to physical meaning. Please do add units to the definitions of each variable.

The units for terms not explicitly mention are obvious based on the other terms and units provided. We feel that adding the units here would clutter the description so we leave it as is.

L295. Indicate the unit of degrees in the equation (for 90).

changed to:

$$\dot{b}_{icecliff} = \dot{b}_{backwasting} \cos(90^{\circ} - \theta)$$

L312. Verb tense issue: '... the curve fits ... are calculated ...'

Corrected to:

"For the best case the curve fits through debris thickness are calculated using the median of data from the 50-m elevation bins (Fig. 5)."

L317. 'ice cliffs' should be singular (ice cliff slopes) or possessive (ice cliffs' slopes)

Changed to: "We also apply ±1σ range for sub-debris melt and ice cliff backwasting rates, and a ±1σ range for ice cliff slopes."

L318. Doubled %%

removed one %

L340. Please do not start this sentence with 'And'.

The sentence now reads:

"Debris consistently 1 m thick was observed just out of the study area but still in moraine 9 at 730 m a.s.l.."

L346. A suitable reference for this is (Mertes, Thompson, Booth, Gulley, & Benn, 2016).

Reference added.

L383. Nice simple inference worth testing further. Most likely this relates to the difficulty of mobilizing debris, see e.g. (Moore, 2017).

Thank you.

"This implies that ice cliff coverage could vary with debris thickness or a variable that co-varies with debris thickness (Table 4)."

Changed to:

"This implies that ice cliff coverage could vary with debris thickness or a variable that co-varies with debris thickness, like the mobility of debris (Moore, 2018; Table 4)."

L392. It's not immediately clear what the values in parentheses mean. Are these the lower/higher estimates? Just make it clear in the first instance.

Good catch. The sentence now reads:

"When averaged across the entire study area, 8% of melt is derived from sub-debris melt and 26 (with extreme bounds of 20 , 40)% from ice cliff melt. "

L421. Is this in cm? This content is a bit unrelated; the consistent decline in sub-debris melt is not unexpected for many other reasons as well, which h* just indicates in aggregate.

Yes, corrected 'm' to 'cm.' We are simply drawing attention to the consistency of the h* from Kennicott and similarity of Ostrem's curves from glaciers at similar latitudes with the global compilation and the fact that sub-debris melt is reduced as debris thickens. We do understand the need for a change here so we leave the text as is.

L428. Awkward comma placement. Best to get rid of 'Becuase' here, and connect to the next sentence (which begins with 'But'). Again, see (Moore, 2017) for a review of these processes.

This section was removed to streamline the discussion follow both reviewer's comments.

L423-446. This is interesting content but largely conjecture and lacking a synthesis – so there are many possible reasons for heterogeneity in cliff backwasting rates as you measured, but what does it mean for science? What is the point? That we need large N? Or high-quality measurements and models? Or...?

We re-wrote this section following the reviewer comments. Ultimately we need to discuss the trends or lack thereof in our ice cliff measurements. We chose to present that discussion in a form that presents a few hypotheses and support those hypotheses with references. They are inferences that could be further explored by the community.

L457. This sentence undermines itself: ‘Our method works if you correct it for bias.’ I think the point here is that your method presents the spatial variability of ice cliff areas very well, even if it underestimates the total cliff area somewhat; this spatial variability is key for you to derive the subdebris melt estimates!

We adjust the wording following the reviewer’s suggestion:

“Our automated methods provide an accurate estimate of ice cliff area as it varies across a large debris-covered tongue. Both the *ABT* and *SED* ice cliff delineation methods underpredict ice cliff area somewhat.”

It would be nice to see how consistent those biases are between the distinct evaluation patches, possibly as a panel in the SuppMat. A lot of content, time and effort has gone into the cliff mapping method and it would be nice to see the high quality results in more detail there.

We appreciate the reviewer’s desire for more analyses but frankly we do not see how this is needed. Perhaps a comparison between ice cliff delineation methods should be performed with independent operators?

Considering that the reviewer in their introduction noted about their review:

“There are a few more substantive comments, but none that require additional analysis.”

We chose not to provide more analyses to a supplemental with 25 figures, one that the other reviewer finds too long already.

L489. Great synthesis. My only suggestion would be to also clearly acknowledge that ice cliffs greatly enhance the overall melt rates for the debris-covered area; as presently written, the implication is that one only has to account for the increasing debris cover to get a reasonable melt estimate; this would underestimate melt by 26% in your results. Clearly the debris dominates the glacier-wide melt rate and wrt elevation, but also it is clear that you need to take cliffs into account somehow.

As this paragraph is written in no way does it imply that ice cliffs should be neglected. Rather it simply states that area-averaged melt rates are dominated by debris that reduced melt relative to bare ice. Perhaps this is written in a fashion that is not typical for ice cliff studies but it is still accurate. There is a running misconception in the community and the literature where % melt contribution is confused with the absolute melt contribution.

To assuage the reviewer we add this sentence in the new conclusion:

"While ice cliffs should not be neglected, our analysis suggests that the community should focus more energy on quantifying debris thickness and sub-debris melt rates as they vary across individual glaciers and regions."

L515. Convincing hypothesis tests above. For completeness, you may as well perform a back-of-envelope for cliffs and streams to emphasize that, even poorly-constrained, these features cannot source sufficient energy for melt to be the only driver of the ZMT.

We follow this advice and include this new paragraph:

"While we do not explicitly document the melt rate of ponds and streams we follow Kraaijenbrink et al. (2017)'s approach and assume all melt hotspots melt at the same rate as ice cliffs. Using this approach, in order for melt hotspots in the *ZMT* to compensate for the insulating effects of debris, melt hotspots would need to cover 90% of the glacier surface, which they assuredly do not. This again suggests that ice cliffs (and other melt hotspots) do not control the location of the *ZMT*."

L515-517. Agreeing that melt is not maximized in the ZMT, isn't it also clear that cliff and debris melt is maximized (although still less than for clean ice) leading into the ZMT? I.e. aren't cliffs and high subdebris melt rates important drivers of the reduced ice flux into the ZMT?

Interesting idea but not what we consider to be the key process here. We address this idea in a new section at the end of the discussion that ties the continuity equation back into the manuscript.

L519. 'debris-covered glacier termini' appears to have been accidentally used twice.

Corrected to: "On debris-covered glacier termini, debris tends to thicken downglacier (e.g., Anderson and Anderson, 2018) as is the case for Kennicott Glacier**."**

L522. (Bisset et al., 2020) examined selected glaciers across HMA, not only in the Everest region

Corrected to: "This leads to the expectation that sub-debris melt rates will decline towards the terminus reversing the mass balance gradient, similar to the results and conclusions for selected glaciers across High Mountain Asia (Bisset et al., 2020)."

L524. The 42% figure comes from nowhere – do you mean Ngozumpa via Thompson et al (2016)? Anyways I think the suggestion is a good simplified debris thickness representation – if you can figure out how to estimate the apportioning of melt to cliffs!

We agree and removed that sentence, though it was referring to Kennicott Glacier and the elevation binned percentages in Fig. 12. The new paragraph is here:

"On debris-covered glacier termini, debris tends to thicken downglacier (e.g., Anderson and Anderson, 2018) as is the case for Kennicott Glacier**.** This leads to the expectation that sub-debris melt rates will decline towards the terminus reversing the mass balance gradient, similar to the results and conclusions for selected glaciers across High Mountain Asia (Bisset et al., 2020). The overall mass balance profile for the summer of 2011 (Fig. 12) shows this Østrem's curve like pattern, suggesting that it is more strongly influenced by debris thickness than melt hotspots. Future efforts to represent the effects of ice cliffs on glacier mass balance at the regional scale should consider using a modified debris thickness-melt relationship with a percentage enhancement based on empirical relationships between debris thickness and ice cliff melt contribution. "

L530. To my knowledge it is the first time that melt has been quantified for a debris-covered tongue in Alaska, and one of the few times it has been done convincingly, with in situ measurements, for a debris-covered area globally. Nice work.

Thank you.

L531-569. Please rework this long list (12 items!) of bullet points into cohesive paragraphs.

The conclusion was re-worked into paragraphs.

L572. Please just archive the data in a repository. You can still force people to request them or let you know what they intend to use the data for.

We are making the in situ data available openly. The DOI is in the manuscript now.

Table 1. The values for ice cliff backwasting in the 'min' and 'max' cases do not seem to correspond to Table 2 or Figure 7 (these would be 4.6 and 9.6). Which values did you use?

Good catch thank you. For Table 1 it is the values in your parentheses. We changed the labels in Figure 1 to clarify that these are for uncertainty estimates. We also made it clear in Table 2 that those min and max values are for the in situ measurements.

Table 4. Note that (Thompson, Benn, Mertes, & Luckman, 2016) lumped all cliff-associated influence by necessity, whether due to cliffs/ponds/streams etc.

Added a note to the table:

"***Combined contribution from ice cliffs, ponds, and streams"

Figure 1. On panel (c) the legend need some work to show the variation (dH/dt) and units clearly.

We have now included this text in the caption: "The units for the legend are above the labeled colors."

Please also consider using a proper color ramp – I know it is a pain in QGIS.

We do not see how this change will actually improve the legibility of the figure. With a continuous colormap it will be nearly impossible to see the specific labels for the colors (a common problem using continuous colormaps). As it is we find that the legend is quite legible. Additionally reviewer 1 did not have any issue with these legends so we choose not to follow this suggestion.

I don’t think there is a need for the statistics from the Das et al (2014) study in the caption, but if you want to include them, it’s not clear what you mean by the mean error and 1 std – is the ‘mean’ the glacier-wide error of the mean, and 1 std (can be sigma) the standard deviation across the glacier? This is easily misunderstood.

We remove the statistics as requested.

“Map of the general study area with dH (dt)$^{-1}$ from 1957 to 2004 see Das et al. (2014) (mean error 0.04 m yr^{-1} and 1 std 0.15 m yr^{-1} based on 3 km^{2} area within 4 km of the modern terminus).”

Changed to

“Map of the general study area with dH (dt)$^{-1}$ from 1957 to 2004 see Das et al. (2014).”

We include the statistics here because of the extra emphasis on the need for uncertainty to be defined in previous reviews.

Figure 3. Very nice synthesis.

Thank you!

Figure 4. As for figure 1, the legend in panel (a) needs to be tidied.

We think the non-continuous colormap is much more legible than a continuous colormap as the reviewer suggests. Because ourselves and the other reviewer did not find that this was a problem we choose not to make any changes here.

Figure 5. Correction to caption text: ‘The red bars are the median...’.

Corrected.

For completeness of the manuscript itself, and also as a nice comparison to this relationship, I would prefer to see the relationships of debris thickness with elevation for the other moraines here.

We appreciate and understand the desire for this but do not this change will improve the manuscript as it will overwhelm the reader as per the comments of Reviewer 1. We now reference the supplemental figure where readers can see the data from each of the individual medial moraines

Figure 6 caption. ‘... is smaller than the marker ...’. The RMSE units are presumably cm w.e. d^-1?

Corrected.

Figure 7. I suggest to indicate ‘ZMT’ next to the arrow for clarity.

ZMT was added to this figure as well as figures 2, 5 and 6.

In (b) the axis labels are not terribly clear: ‘aspect’ is not labelled anywhere (nor the units) and the ice cliff backwasting axis values are a bit confusing due to their location.

This is a good catch. We added ‘degrees’ to the ‘aspect’ labels. We rotated the backwasting rate labels so it is clear that they are different from the aspect labels. The caption does mention aspect and we think that adding the words ‘Aspect’ to panel ‘b)’ will confuse the reader.

Figure 8. In some respects the results without morphological opening look even better, because the opening has also removed thin slivers of true ice cliff area. Did you try a connected-pixels morphological clean? This would eliminate (for example) ‘cliffs’ with less than 10 pixels, and would generally leave the thin cliffs unmodified. Perhaps you are happy with the current performance, but it’s just a suggestion.

Interesting suggestion which we would love to explore further but we do not see the reason now for an additional sensitivity test for this manuscript which is already full of analyses. I am sure there is a good argument for using other approaches as well. Thank you for bringing it to our attention.

Figure 9. In the caption, there is mention of ‘thin red lines’ but I don’t see these anywhere. Perhaps use a different colour for these?

We adjusted the caption to better explain the thick and thinner red lines.

Figure 10. Please indicate the elevation bin size for the hypsometry.

Added to the caption: “All panels use 20 m elevation bins.”

Figure 11. Why not delineate the ZMT here using elevation contours (thus corresponding directly to the rest of the paper)? Otherwise I find myself wanting to flip back several pages to see where the contours are, etc.

The ZMT is defined early on is defined by the area with thinning less than -1.2 m/yr. Because of the complexity of the topography on the glacier surface following the reviewer’s comment will make the figure much less legible and actually detract from the legibility of the figure. Reviewer 1 had no issue with this and the ZMT is labeled clearly in the figures. For these reasons we choose not to follow this suggestion.

Figure 12. Small typo: ‘84.1% of estimates are within the grey shaded band.’

Thank you, corrected.

Debris cover and the thinning of Kennicott Glacier, Alaska: in situ measurements, automated ice cliff delineation and distributed melt estimates

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Abstract. Many glaciers are thinning rapidly beneath melt-reducing debris cover, including the Kennicott Glacier in Alaska. The zone of maximum thinning at Kennicott Glacier is located under debris. Scattered within the debris cover, melt hotspots, like ice cliffs, locally increase melt rates. We explore the roles of debris and ice cliffs in controlling rapid thinning under thick debris at Kennicott Glacier.

We collected abundant in situ measurements of debris thickness, sub-debris melt, and ice cliff backwasting allowing for extrapolation across the debris-covered tongue (the study area and the lower 24.2 km^2 of the 387 km^2 glacier). A newly-developed automatic ice cliff delineation method is the first to use only optical satellite imagery. The Adaptive Binary Threshold method accurately estimates ice cliff coverage even where ice cliffs are small and debris color varies.

There is more debris-covered ice in Alaska than any other region on Earth. Through our efforts Kennicott Glacier is now the first in glacier in Alaska and the largest globally where melt across its debris-covered tongue has been rigorously quantified. Kennicott Glacier also exhibits the highest fractional area of ice cliffs (11.7 %) documented to date. Ice cliffs contribute 26% of total melt across the glacier tongue. Although the *relative* importance of ice cliffs to area-average melt is significant, the *absolute* area-averaged melt is dominated by debris.

At Kennicott Glacier, glacier-wide melt rates are not maximized in the zone of maximum thinning. In order to explain the rapid thinning under debris, a decline in ice discharge through time is necessary.

~~**Abstract.** Many glaciers are thinning rapidly beneath debris thick enough to reduce melt rates relative to bare ice. Melt hotspots within otherwise continuous debris cover increase area-averaged melt rates, counteracting the melt suppressing effects of debris. Kennicott Glacier, a large Alaska glacier, is thinning most rapidly, upglacier from its terminus, but under insulating debris cover. We explore the role of debris and ice cliffs in controlling this zone of maximum thinning.~~

~~We provide abundant in situ measurements of debris thickness (109), sub-debris melt (74), and ice cliff backwasting (60). We also develop a new, accurate method to automatically delineate ice cliffs using high-resolution panchromatic satellite imagery. We then use empirical relationships, to estimate melt area-averaged melt across the lower 8 kilometers of the glacier.~~

~~Ice cliffs cover 11.7% of the debris-covered tongue, the most of any glacier studied to date, which contribute 26% of melt in study area with a mean debris thickness of only 13.7 cm. While the relative importance of ice cliffs to melt increases as debris thickens downglacier, the absolute magnitude of area-averaged melt declines towards the terminus.~~

~~The primary control on area-average melt rate across the zone of maximum thinning appears to be debris thickness, but maximum surface melt does not align with the zone of maximum thinning. We therefore suggest that the decline in ice discharge from upglacier is the vital control defining the zone of maximum thinning.~~

Keywords: mass balance; WorldView; remote sensing; global; climate change; debris-covered~~backwasting; Østrem's curve, debris-covered glacier~~

1 Introduction

Loose rock (debris) is common on glacier surfaces globally and is especially abundant on glaciers in Alaska (Scherler et al., 2018; Herreid and Pellicciotti, 2020). Where debris is thicker than a few centimeters it insulates the underlying ice, leading to the reduction of melt rates (Østrem, 1959; we refer to 'thick debris' as any debris that reduces melt rates relative to bare-ice melt rates). Adding to this insulating effect, debris covers are expanding for many glaciers even as glaciers contract in response to rising temperatures (e.g., Tielidze et al., 2020). Expanding and thickening debris cover (Banerjee, 2017; Gibson et al., 2017) should reduce glacier thinning relative to glaciers without debris, but the melt-reducing effect of debris is not always apparent in the observed thinning patterns of glaciers (e.g., Kääb et al., 2012; Gardelle et al., 2013). In High Mountain Asia many debris-covered and debris-free glaciers are thinning at similar rates (e.g., Nuimura et al., 2012; Agarwal et al., 2017; Lamsal et al., 2017; Brun et al., 2018; Wu et al., 2018). This apparent paradox, in which rapid thinning is occurring under thick debris cover is known as the 'debris-cover anomaly' (Pellicciotti et al., 2015) and has also been documented in the European Alps (Mölg et al., 2019).
~~Loose rock (debris) is common on glacier surfaces globally and is especially abundant on glaciers in Alaska (Scherler et al., 2018). Where debris is thicker than a few centimeters it insulates the underlying ice, leading to the reduction of melt rates (Østrem, 1959; we refer to 'thick debris' as any debris that reduces melt rates relative to bare-ice melt rates). Adding to this insulating effect, debris is expanding for many glaciers even as they contract in response to climate warming (e.g., Tielidze et al., 2020). Expanding and thickening debris cover should reduce glacier thinning relative to glaciers without debris. But the melt-suppressing effect of debris is not always apparent the observed thinning patterns of glaciers even when debris is thick and debris coverage is extensive (e.g., Kääb et al., 2012; Gardelle et al., 2013). In High Mountain Asia many debris-covered and debris-free glaciers are thinning at similar rates (e.g., Kääb et al., 2012; Brun et al., 2018). This apparent paradox, in which rapid thinning is occurring under insulating debris cover is known as the 'debris-cover anomaly' (Pellicciotti et al., 2015). It has been documented in both Asia and in the European Alps (Nuimura et al., 2012; Agarwal et al., 2017; Lamsal et al., 2017; Wu et al., 2018; Mölg et al., 2019).~~

The 'debris-cover anomaly' is occurring in Alaska, but to date, research into the effect of debris on glaciers in Alaska has been scant. A close look at previously published glacier thinning patterns from southeast Alaska reveals that maximum thinning rates within single glaciers are similar whether debris is present or not (Figs. 1 and 2; Berthier et al., 2010; Das et al., 2014). Kennicott Glacier in the Wrangell Mountains is an example where rapid thinning is occurring under debris cover (Figs. 1 and 2). Greater surface elevation changes are documented from the Kennicott debris-covered tongue than from any portion of the largely debris-free Nabesna Glacier, north of Kennicott Glacier (Fig. 2).

This brings us to our overarching question: *Why does the maximum thinning of Kennicott Glacier occur under debris at rates similar to nearby debris-free glaciers?* To guide our analysis, we define a zone of maximum thinning or *ZMT* where Kennicott Glacier thinned at an average rate greater than 1.2 m yr^{-1} between 1957 and 2004 (Figs. 1 and 2; Das et al., 2014). For Kennicott Glacier, thinning rates this high only occur within 4 kilometers of the terminus and under debris. The *ZMT* occupies a 2-km down-glacier by 3.5-km across-glacier portion of the debris-covered tongue. The *ZMT*, as defined, is consistent with maximum thinning rates between 2000 and 2007 based on lidar profiles (Fig. 2; Das et al., 2014).
~~The 'debris-cover anomaly' may in fact be a global phenomena. A close look at previously published glacier thinning patterns from the Wrangell Mountains of southeast Alaska reveals that maximum thinning rates from within single glaciers are similar whether debris is present or not (Figs. 1 and 2; Berthier et al., 2010; Das et al., 2014). This is a compelling because the Wrangell Mountains occur at 61 to 62 deg. N, a latitude and in a region where the effects of debris on glacier mass balance has received almost no attention.~~

~~One of the glaciers within the Wrangell Mountains that is thinning rapidly under debris cover is Kennicott Glacier (Figs. 1 and 2). Greater surface elevation changes are documented from the Kennicott debris-covered tongue than from any portion of the largely debris-free Nabesna Glacier, north of Kennicott Glacier (Fig. 2). Why does the maximum thinning of Kennicott Glacier occur under debris at rates similar to nearby debris-free glaciers? To aid our analysis, we define a zone of maximum thinning or *ZMT* where Kennicott glacier thinned at an average rate greater than 1.2 m yr^{-1} between 1957 and 2004 (Figs. 1 and 2; Das et al., 2014). For Kennicott Glacier, thinning rates this high only occur within 4 kilometers of the terminus and under debris. The *ZMT* occupies a 2-km down-glacier by 3.5-km across-glacier portion of the debris-covered~~

tongue. The *ZMT*, as defined, is consistent with maximum thinning rates between 2000 and 2007 based on lidar profiles (Fig. 2; Das et al., 2014).

The continuity equation for ice is fundamental for understanding how glaciers thin, with or without debris. It can be formulated as:

$$\frac{dH}{dt} = \dot{b} - \nabla \cdot Q \quad , \qquad (1)$$

where H is the ice thickness, t is time, $\dot{b}$ is the annual specific mass balance (or loosely ice melt in the ablation zone), Q is the column integrated ice discharge (or loosely ice dynamics; Fig. 3), x is the east-west direction, and y is the north-south direction. Constraining $\dot{b}$ on debris-covered glaciers is particularly difficult due to the presence of ice cliffs, ponds, and streams within debris covers. The annual specific balance in the ablation zone can be sub-divided,

$$\dot{b} = \dot{b}_s + \dot{b}_e + \dot{b}_b \qquad (2)$$

where $\dot{b}_s$ is the annual surface ablation, $\dot{b}_e$ is the annual englacial ablation, and $\dot{b}_b$ is the annual basal ablation rate. Surface ablation typically dominates $\dot{b}$ in most non-polar settings. We neglect the effects of $\dot{b}_e$ and $\dot{b}_b$ because their contribution to rapid thinning is likely small and it is not yet possible, to quantify them within and under debris-covered tongues (see Benn et al., 2017). Building from Eq. (1), $\dot{b}_s$ is negative in the ablation zone, and therefore shifts $\frac{dH}{dt}$ towards negative values, thinning the glacier. In the ablation zone, the sum of $-\nabla \cdot Q = \frac{-dQ_x}{\partial x} - \frac{\partial Q_x}{\partial y}$, ($x$ is the along flow direction, and y is the across flow direction), or the ice emergence velocity tends to be positive due to the slowing of ice downglacier. This ice emergence velocity counters surface lowering due to melt.

where $\dot{b}_s$ is the annual surface ablation, $\dot{b}_e$ is the annual englacial ablation, and $\dot{b}_b$ is the annual basal ablation rate. Surface ablation typically dominates $\dot{b}$ in most non-polar glacial settings. We neglect the effects of $\dot{b}_e$ and $\dot{b}_b$ because their contribution to rapid thinning is likely small and it is not yet possible, to quantify them within and under debris-covered tongues. Building from Eq. (1), $\dot{b}_s$ is negative in the ablation zone, and therefore shifts $\frac{dH}{dt}$ towards negative values, thinning the glacier. In the ablation zone, the sum of $\frac{-dQ}{dx} - \frac{dQ}{dy}$ tends to be positive due to slowing ice flow. This ice emergence velocity counters surface lowering due to melt.

Two common explanations for the debris-cover anomaly follow from Eq. (1), which are not mutually exclusive (Immerzeel et al., 2014; Vincent et al., 2016; Brun et al., 2018). First, it is possible that melt $\dot{b}$, when averaged over glacier widths is higher than we expect from the melt reducing debris alone, therefore leading to rapid thinning. Ponds and ice cliffs have been documented to locally increase melt rates on debris-covered glaciers by an order of magnitude compared to adjacent melt rates measured from under debris (e.g., Immerzeel et al., 2014). M*elt hotspots* such as ice cliffs, ponds, streams, and thermokarst counter the insulating effects of debris by raising area-averaged melt rates (e.g., Kirkbride, 1993; Sakai et al., 2002; Reid and Brock, 2014; Miles et al., 2018). Conceptually, melt hotspots perturb the area-averaged melt rate from a melt rate solely defined by the insulating effects of debris (lower melt rates) towards a melt rate solely defined by the melt of bare-ice (higher melt rates). The degree to which these hotspots increase area-averaged melt rates, is an area of active debate within the community. Second, increased melting upglacier of the debris leads to glacier thinning an reduced ice flow to debris-covered portions of glaciers. This leads to reduced ice emergence rates and locally amplified thinning (e.g., Nye, 1960; Vincent et al., 2016).

Two common explanations for the debris-cover anomaly follow from Eq. (1), which are not mutually exclusive (Immerzeel et al., 2014; Vincent et al., 2016; Brun et al., 2018). First, it is possible that surface melt $\dot{b}$, is higher than we expect from the melt-reducing debris alone, therefore leading to rapid thinning. Ponds and ice cliffs can locally-increase melt rates by an order of magnitude compared to adjacent melt rates measured under debris (e.g., Immerzeel et al., 2014). *Melt hotspots* such as ice cliffs, ponds, streams, and thermokarst counter the insulating effects of debris by raising area-averaged melt rates (e.g., Kirkbride, 1993; Sakai et al., 2002; Reid and Brock, 2014; Miles et al., 2018). Conceptually, melt hotspots

perturb the area-averaged melt rate from a melt rate solely defined by the melt-reducing effects of debris towards a melt rate solely defined by the melt of bare-ice. The degree to which these hotspots increase area-averaged melt rates is an area of active debate. Second, less-positive surface mass balance upglacier from the zone of maximum thinning leads to reduced ice flow into the *ZMT*. Reduced ice flow leads to declining ice emergence rates and locally amplified thinning (e.g., Nye, 1960; Vincent et al., 2016). We revisit the continuity equation for ice at the end of the discussion.
~~Kennicott Glacier holds exceptional potential for reveling the role of melt hotspots in debris-covered glacier thinning. In the last 8 kilometers of Kennicott Glacier more than 10 thousand ice cliffs are scattered within otherwise continuous debris (Anderson, 2014). If melt hotspots are the sole control on the *location and magnitude* of the zone of maximum thinning or *ZMT* for Kennicott Glacier then we should expect melt rates (averaged across the glacier width) from across Kennicott Glacier to be maximized there. Here, we to address three questions: (1) *What is the surface mass balance across the debris-covered tongue and zone of maximum thinning of Kennicott Glacier during the summer of 2011?* 2) *Do ice cliffs maximize glacier-wide melt in the zone of maximum thinning during the summer of 2011?*~~

Kennicott Glacier provides an opportunity to test the importance of melt hotspots in controlling debris-covered glacier thinning: more than 15-thousand ice cliffs are scattered within otherwise continuous debris (Anderson, 2014). If melt hotspots are the only control on the location of the *ZMT* for Kennicott Glacier then we should expect melt rates (averaged across the glacier width) to be maximized there. Here, we address two questions: (1) *What is the surface mass balance across the debris-covered tongue and zone of maximum thinning of Kennicott Glacier?*; and 2) *Do ice cliffs maximize glacier-wide melt in the zone of maximum thinning?* To address these questions, we quantify the role of ice cliffs and debris in setting the melt pattern across the debris-covered tongue of Kennicott Glacier.

Partly because of the significant effort required, in situ measurements from debris-covered glaciers are abundant on only a few keystone glaciers in the Himalaya (e.g., Lirung, Ngozumpa, and Khumbu Glaciers; Benn et al., 2012; Immerzeel et al., 2014) and European Alps (e.g., Miage and Zmutt Glaciers; Brock et al., 2010; Mölg et al., 2019). The lack of in situ observations from a range of debris-covered glaciers hinders the inclusion of debris cover in global projections of glacier change. Measurements from debris-covered areas in overlooked regions like Alaska are therefore a pressing need.

Using abundant in situ measurements, we estimate the distributed melt rate across the debris-covered tongue of Kennicott Glacier for the summer of 2011. We measured debris thickness, debris conductivity, air temperature, sub-debris melt rates, and ice cliff backwasting rates. We focus on the effects of ice cliffs, which are abundant at Kennicott Glacier, leaving a detailed examination of other melt hotspots for another contribution. Despite this, we do still consider the general role of melt hotspots in sensitivity tests in the discussion.

In order to generate distributed melt estimates on debris-covered glaciers, we must delineate ice cliff extent. Quantifying their extent efficiently and accurately is difficult. Previous efforts to delineate ice cliffs have largely relied on the manual digitization of remotely-sensed data (Sakai et al., 1998; Han et al., 2010; Thompson et al., 2016; Watson et al., 2017; Han et al., 2010; Thompson et al., 2016; Watson et al., 2017). Automatic methods include object-based image analysis based on images derived from unmanned aerial vehicles (e.g., Kraaijenbrink et al., 2016) and principal component analysis using near-infrared and infrared satellite bands (Racoviteanu and Williams, 2012). Herreid and Pellicciotti (2018) most recently developed an automatic method to delineate ice cliffs using 5 meter digital elevation models (DEMs). Despite the efforts of projects like the ArcticDEM (Porter et al., 2018), glacier coverage with high-resolution DEMs (or high-resolution hyperspectral imagery) is still rarer than coverage with high-resolution optical-satellite imagery.

Here we develop a novel, automatic method to delineate ice cliffs using only high-resolution WorldView-1 satellite imagery. We use this method to delineate the abundant ice cliffs on the surface of Kennicott Glacier. We combine our in situ measurements and remotely delineated ice cliffs to quantify surface melt rates in a distributed fashion across the zone of maximum thinning, thereby addressing the questions outlined above.

~~To address these questions, we quantify the role of ice cliffs and sub-debris melt across the debris-covered tongue of Kennicott Glacier during the summer of 2011. We limit our scope to ice cliffs and sub-debris melt, leaving an examination of surface ponds and streams as later contributions. Our analysis is rooted in the collection of abundant in situ data from the glacier surface, including: debris thickness, sub-debris melt rates, and ice cliff backwasting rates. In addition to helping address the questions raised above, these in situ measurements, from this latitude and Alaska, are vital for developing a global perspective on glacier response to climate change as well as the next generation of global glacier models incorporating the effects of debris cover.~~

~~To determine the mass balance pattern within the debris-covered tongue, ice cliff extent must be quantified. We therefore present and apply a new method for remotely delineating ice cliffs using high-resolution WorldView 1 orthoimages. We~~

~~combine our in situ measurements and remotely delineated ice cliffs to quantify surface melt rates in a distributed fashion across the zone of maximum thinning, thereby addressing the questions outlined above.~~

1.1 Study glacier

Kennicott Glacier is a large (387 km^2) broadly south-southeast facing glacier on the south side of the Wrangell Mountains. The glacier exists across a 4600 m elevation range between 5000~~4996~~ and 400 m a.s.l. (Fig. 1~~; 387 km^2 area~~). For comparison, Khumbu Glacier, in Nepal, has an area of 26.5 km^2 and spans an elevation range of 3950 m from 8850 to about 4900 m a.s.l. (Pfeffer et al., 2014). Kennicott Glacier covers almost 15 times more area than the Khumbu Glacier. ~~and our study area, the debris-covered tongue of Kennicott Glacier (24.2 km^2), is only slightly smaller than Khumbu Glacier itself.~~ The main trunk of Kennicott Glacier is 42 km long and is joined by two ~~primary~~ tributaries, the Root and the Gates Glaciers. Kennicott Glacier has only retreated 600 meters since its maximum Little Ice Age extent in 1860 (~~Figure 4;~~ Rickman and Rosenkrans, 1997~~; Das et al., 2014; Larsen et al., 2015~~).

As of 2015, approximately 20% of Kennicott Glacier was debris-covered. At elevations below the equilibrium-line altitude at about 1500 m a.s.l. (Armstrong et al., 2017), nine~~9~~ medial moraines are identifiable within the debris-covered tongue. These medial moraines form primarily from the erosion of hillslopes above the glacier and express themselves as stripes on the glacier surface (Anderson, 2000)~~(Anderson, 2000)~~. Above 700 m a.s.l., debris is typically about one clast thick (Anderson, 2014). Below this elevation debris thickness tends to increase downglacier through the debris-covered tongue (Anderson and Anderson, 2018). The medial moraines coalesce in the last 7 km of the glacier where ice cliffs, surface ponds, and streams are scattered within otherwise continuous debris cover ~~(Anderson, 2014)~~.

2 Methods

Our methods fit into three broad categories: 1) in situ measurements; 2) automatic ice cliff delineation; and 3) distributed melt rate estimates. In situ measurements were made within the broad study area shown in Figure 1c. Distributed melt estimates on the other hand are made across the delineated medial moraines shown in Figure 4a. In total this 24.2 km^2 study area is referred to as the 'debris-covered tongue' and is similar in size to the entirety of Khumbu Glacier. In situ measurements were all made within the study period from 18 June to 16 August 2011. All melt rate measurements are in ice equivalent units. We used WV stereoimagery from 2013 to produce glacier surface DEMs at 5 m spatial resolution using the Ames Stereo Pipeline (Shean et al., 2016), which we use to represent the glacier surface during the study period.

~~Our methods fit into three broad categories: 1) in situ measurements; 2) automatic ice cliff delineation; and 3) distributed melt rate estimates. In situ measurements were made within the broad study area shown in Figure 1C, which is within 8 kilometers of glacier terminus. Distributed melt estimates on the other hand are made across the delineated medial moraines shown in Figure 4A. In total the distributed melt estimates were made over 24.2 km^2 which we consider here to be the 'debris-covered tongue' of the glacier. In situ measurements were all made within the full field campaign duration and study period from 18 June to 16 August 2011. We correct each measured melt rate to represent the full duration of the study period, as described below.~~

2.1 In situ measurements

Determining average melt rates across debris-covered areas is challenging due to the number and diversity of processes involved. Our solution is simple: to make abundant in situ measurements across the study area. For debris to be incorporated into large-scale models, debris thermal properties and onglacier meteorology must also be better documented. We also provide debris thermal conductivities (10 sites) and on-glacier air temperatures (3 sites) as supplementary material (sections S1.4-1.5).

We measured debris thicknesses at 109 sites by digging through the debris to the ice surface (Figs. 5 and S1; after Zhang et al., 2011). Debris measurement locations coincide with the sites where we also measured ice cliff backwasting and sub-debris melt (Figs. 4 and S2-S3). Where debris was thinner than ~10 cm we dug several pits and recorded the average debris thickness. Uncertainty estimates were based on the repeated measurement of debris thickness at 52 ablation stakes.

We measured sub-debris melt at 74 locations (Figs. 4 and S4-S6). At each site, we removed debris, installed ablation stakes and then replaced the debris. We placed stakes in debris up to 40 cm thick. Sub-debris melt ($\dot{b}_{debris}$) was measured by removing the debris and measuring ice surface lowering (Fig. 6). We estimated uncertainty using data from all ablation stakes based on the uncertainty in marking and measurement as well as the tilt of the stake. We assume a ±2 cm error in the distance measurement along ablation stakes. The average-measured tilt of the ablation stakes was 5° from vertical. Bare-ice melt rates were also measured at several locations in the northeastern portion of the study area on the Root Glacier.

We measured in situ backwasting rates from 60 ice cliffs (Figs. 7 and S7-S8). We made repeat horizontal distance measurements between the upper ice cliff edge and a stationary marker (in a moving reference frame; after Han et al., 2010). Using all 60 measured ice cliffs, backwasting rate error was estimated based on an assumed uncertainty of ±20 cm applied to the initial and final distance measurements.

Degree-day factors for each melt rate and backwasting rate measurement were calculated using air temperature data from the off-ice meteorological stations (see sections S1.1-S1.2, S1.6 for the full explanation; Hock, 2003). We use hourly 2-m air temperature data from the Gates Glacier and May Creek meteorological stations to estimate the air temperature at each measurement location. Gates Glacier station is located just off the glacier margin at 1240 m a.s.l. and May Creek station is located at an 490 m a.s.l. located 15 km to the southwest of the town of McCarthy (Fig. 1). Each sub-debris melt and backwasting rate measurement was adjusted to represent the full study period using these degree-day factors. These corrections have a negligible effect on the distributed melt estimates. To represent the hypothetical case that no debris was present on the glacier, we also extrapolate bare-ice melt rates across the study area (section S1.6).

~~The presence of ice cliffs, surface lakes, and variations in debris thickness on debris-covered glaciers makes distributed estimates of mass balance difficult. In order to remedy this issue we make abundant in situ measurements of debris thickness, sub-debris melt, and ice cliff backwasting across the glacier tongue from late June to late August 2011. Partly because of the significant effort required to make in situ measurements, mass balance research of debris-covered glaciers has been focused on a few keystone glaciers in the Himalaya (e.g., Lirung, Ngozumpa, and Khumbu Glaciers; Benn et al., 2012; Immerzeel et al., 2014) and European Alps (e.g., Miage and Zmutt Glaciers; Brock et al., 2010; Mölg et al., 2019). Sparse in situ observations, relative to bare-ice glaciers, mean that global projections of glacier change cannot yet robustly incorporate the effects of debris cover. Measurements from debris-covered glaciers in new regions like Alaska are therefore needed. In order for debris-covered glacier mass balance models to be applied regionally, basic debris properties and the meteorology above the debris must also be measured. In addition to the measurements presented in the main text, we also present on-glacier air temperatures and debris thermal conductivities from the summer of 2011, which we provide as supplementary, supporting material.~~

~~**2.1.1 Debris thickness**~~

~~We measured debris thicknesses at 109 sites. Debris measurement locations coincide with the sites that we also measured ice cliff backwasting and sub-debris melt (Fig. 4; Supplemental material). We measured thicknesses by digging through the debris to the ice surface (after Zhang et al., 2011). Where debris was thinner than ~10 cm we dug 5 pits and recorded the average debris thickness. While we did not measure debris thickness below 450 m a.s.l., visual inspection from across the proglacial pond suggests that debris exceeded 1 m above some ice cliffs. The mean uncertainty of the debris thickness measurements is ±0.3 cm, with a standard deviation of ±1.8 cm, and a maximum error of ±6.7 cm (Fig. 5). Error estimates were based on repeated measurements, but measurement error is a negligible compared to the changes in debris thickness down and across the glacier.~~

~~**2.1.2 Sub-debris melt**~~

~~We measured sub-debris melt at 74 locations (Fig. 4). At each site, we removed debris, installed ablation stakes and then replaced the debris (Supplemental Figure 1). We placed stakes in debris up to 40 cm thick. Sub-debris melt ($\dot{b}_{debris}$) was measured by removing the debris and measuring ice surface lowering. The mean uncertainty in the sub-debris melt rates was ± 0.1 cm d^{-1}, the standard deviation was 0.05 cm d^{-1}, and the maximum error was 0.25 cm d^{-1} for the three ablation states with the shortest measurement period of 8 days. These measurement uncertainties are small compared to the changes in melt rate with debris thickness (Fig. 6).~~

~~Because melt measurements were made over different time periods we corrected each measurement to represent the full study period. A degree-day factor for sub-debris melt was therefore calculated for each measurement (see supplemental for the full explanation; Hock, 2003). This has a negligible effect on the curve fits we apply below, and the uncertainty added is well within the uncertainty bounds of the distributed melt estimates. We apply this correction non-the-less for completeness.~~

~~**2.1.3 Ice cliff backwasting**~~

Previous studies have estimated ice cliff backwasting rates as they vary in space using DEM-differencing, models, and in-situ measurements. These approaches have shown that 1) ice cliff survivability varies strongly with aspect at lower latitude (Sakai et al., 2002; Buri and Pellicciotti, 2018); 2) ice cliff melt rates are highly sensitive to cliff slope (Reid and Brock, 2014); 3) local topography plays an important role in local ice cliff backwasting rates (Steiner et al., 2015); and 4) ponds allow for the long-term persistence of ice cliffs (e.g., Brun et al., 2016; Miles et al., 2016). On Kennicott Glacier, we take advantage of a rich dataset of in-situ backwasting rates from 60 ice cliffs.

We made repeat horizontal distance measurements between the upper ice cliff edge and a stationary marker (in a moving reference frame; after Han et al., 2010). Ice cliff backwasting rates were extrapolated to the full study period by calculating a degree-day factor for each ice cliff using data from the off-ice meteorological stations (see supplemental for full methods). The mean error of the ice cliff backwasting rates is ±0.5 cm d^{-1} (Fig. 7; Supplemental Figure 9). Maximum error is ±1 cm d^{-1} for 10 cliffs that were measured over the shortest interval (21 days). The standard deviation of errors is ±0.2 cm d^{-1}.

2.2 Automated ice cliff delineation methods

We describe an automated algorithm to delineate ice cliffs from optical satellite imagery. We use 0.5 m resolution WorldView (WV) satellite imagery acquired on 13 July 2009 (catalog ID: 1020010008B20800) to delineate ice cliffs across the study area. We use the panchromatic band, which integrates radiance across the visible spectrum and provides the highest-spatial resolution. The 2009 WV image was the closest high-resolution image available in time to the 2011 summer field campaign. Our method for detecting ice cliffs relies on the observation that ice cliffs are generally darker than the debris around them. Ice cliffs, when actively melting, are typically coated with a thin, wet debris film, which appears darker than the adjacent, dry debris in panchromatic-optical imagery (Fig. 8). In addition, steep ice cliffs are often more shaded than nearby lower-sloped debris-covered surfaces.

Ice cliffs are common on debris-covered glacier surfaces and important for the surface mass balance, yet quantifying their extent is difficult. Following Herreid and Pellicciotti (2018), previous efforts to delineate ice cliffs have relied on field mapping (e.g., Steiner et al., 2015) from the manual digitization of remotely-sensed data (Sakai et al., 1998; Han et al., 2010; Thompson et al., 2016; Watson et al., 2017; Han et al., 2010; Thompson et al., 2016; Watson et al., 2017), automatically by object based image analysis locally derived with unmanned aerial vehicles (e.g., Kraaijenbrink et al., 2016) or automatically by principal component analysis using visible near-infrared and shortwave infrared satellite bands (Racoviteanu and Williams, 2012). A new method for the delineation of ice cliffs has also been developed using high-resolution digital elevation models (DEMs) with 5-meter resolution (Herreid and Pellicciotti, 2018). Despite the efforts of projects like the ArcticDEM (Porter et al., 2018), glacier coverage with high resolution DEMs (or high-resolution hyperspectral imagery) is still rarer than coverage with orthoimagery. Here we introduce a new method to delineate ice cliffs using only high-resolution satellite imagery. We use this method to delineate the abundant ice cliffs on the surface of Kennicott Glacier.

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Our method for detecting ice cliffs relies on the observation that ice cliffs are generally darker than the debris around them. Ice cliffs, when actively melting, are typically coated with a thin, wet debris film, which appears darker than the adjacent, dry debris in panchromatic optical imagery (Fig. 8). In addition, steep ice cliffs are often more shaded than nearby lower-sloped debris-covered surfaces.

The workflow we outline relies on open-source Python packages, which facilitates the method's replication and improvement by other researchers. Our workflow consists of three general steps: 1) processing: stretching the image brightness histogram to a suitable range for our ice cliff detection methods; 2) detection: applying an ice cliff detection method; and 3) post-processing: morphologically filtering of the detected ice cliffs (Fig. 8). We apply a linear histogram stretch uniformly across the image, including both the glacier and surrounding off-ice areas. These steps introduce several processing parameters, which we select using a Monte Carlo optimization method. Below, we first present the processing steps, followed by our parameter--optimization procedure.

We use two methods to detect ice cliffs: i) the adaptive binary threshold method (*ABT*; skimage.filters.adpative_threshold tool; e.g., Sauvola and Pietikäinen, 2000); and ii) the Sobel edge delineation method (*SED*; skimage.filters.sobel tool; Richards, 2013). In pre-processing, we use separate saturation stretches (Fig. 85) for each method by applying the exposure function in the scikit-image package (skimage). The different methods perform best with different exposure levels, so we create two separate, ~~separate~~ stretched orthoimages in pre-processing.

The *ABT* approach runs a moving window over the image, calculates the mean-brightness value within that window, and then uses a threshold to binarize the image. Because the brightness threshold varies across the image, the *ABT* approach is less sensitive to changes in illumination and debris color than a global threshold.

The *SED* approach estimates spatial gradients in image brightness. The Sobel operator detects high contrasts between light-colored debris and dark-colored ice cliffs. The saturation stretch applied on the orthoimage causes dark ice cliffs to appear as featureless black regions, which the Sobel operator returns as low gradient values. We apply a brightness-gradient threshold to isolate ice cliffs.

The last step in our processing process is morphological filtering to remove spurious data. Both delineation methods (*ABT* and *SED*) produce false positives from shaded, over-exposed, or textureless debris cover (*SED* only). The *SED* approach produces many false positives, which generally have a characteristic speckled appearance, and often occur in small, isolated groups. We apply morphological opening (Dougherty, 1992) to remove these isolated false positives in both the *ABT* and *SED* approaches (skimage.morphology.opening; Fig. 8). In addition, the *SED* approach creates false positives in regions that have been over-exposed by the saturation stretch and therefore lack texture. For the *SED* method only, we remove these false positives by masking pixels with the maximum brightness.

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To maximize correct ice cliff identification and minimize false positives we compare our ice cliff estimates to hand-digitized ice cliffs from twelve 90,000 m^2 regions. The cumulative area used in the validation dataset was 1.8 km^2, approximately 7.4% of the 24.2 km^2 study area (Fig. 9). There is some operator subjectivity in delineating ice cliffs from satellite imagery, especially for smaller ice cliffs. To minimize this issue, two different human operators independently delineated ice cliffs. As these independent delineations agreed within 3% in their total ice cliff area, we consider operator misidentification to be a negligible source of error.

Seven parameters determine the success of these ice cliff delineation methods: i-ii) the low and high end brightness values used for the saturation stretch; iii-iv) the window size and offset from mean brightness in the *ABT* method, v) the high-end value to use for thresholding in the *SED* method, and; vi-vii) the kernel sizes used in morphological filtering of the *SED* and *ABT* results. To find the best parameter set we use a Monte Carlo approach for multi-objective optimization (Yapo et al., 1998). We ran the ice cliff detection algorithm 2500 times with differing parameter choices. In each iteration, every parameter is randomly selected using uniform-probability distributions over that respective parameters range of possible values (Duan et al., 1992). This method allows us to efficiently test performance across a wide range of parameter values and is sensitive to interaction between selected parameters across their ranges. We evaluate algorithm performance by comparing ice cliff area from the automated routine against the hand-digitized validation dataset. Our optimization simultaneously seeks to maximize true-positive ice cliff delineation, while minimizing false positives and false negatives. We manually inspect the top-performing parameter sets, ranked by Euclidean distance from the origin (Fig. S13), which defines perfect-algorithm performance (section S2; Reed et al., 2013). We chose image processing parameters slightly off the set with the smallest Euclidean distance to reduce false positives (Table S3). We reduce false positives at the expense of true positives because this led to a higher ratio of true positives to false positives, so we are more certain that a given detection is likely to be a real ice cliff.

~~Seven parameters determine the success of these ice cliff delineation methods: i-ii) the low and high end brightness values used for the saturation stretch; iii-iv) the window size and offset from mean brightness in the *ABT* method, v) the high-end value to use for thresholding in the *SED* method, and; vi-vii) the kernel sizes used in morphological filtering of the *SED* and *ABT* results. To find the best parameter set we use a Monte Carlo approach for multi-objective optimization (Yapo et al., 1998). We ran the ice cliff detection algorithm 2500 times with differing parameter choices. In each iteration, every~~

parameter is randomly selected using uniform probability distributions over that respective parameters range of possible values (Duan et al., 1992). This method allows us to efficiently test performance across a wide range of parameter values and is sensitive to interaction between selected parameters across their ranges. We evaluate algorithm performance by comparing ice cliff area from the automated routine against the hand-digitized validation dataset. Our optimization simultaneously seeks to maximize true positive ice cliff delineation, while minimizing false positives and false negatives. We manually inspect the top-performing parameter sets, ranked by Euclidean distance from the origin (see Supplementary Figure 14), which defines perfect algorithm performance (Supplemental materials; Reed et al., 2013). We chose image processing parameters slightly off the set with the smallest Euclidean distance to reduce false positives (Supplementary Table 3). We reduce false positives at the expense of true positives because this led to a higher ratio of true positives to false positives, so we are more certain that a given detection is likely to be a real ice cliff.

2.3 Distributed melt estimates

In order to produce distributed melt estimates, we extrapolate our in situ measurements across the area of the 9 defined medial moraines in Fig. 4. We use empirical curve fits of debris thickness as it varies with elevation and flow path (i.e., by medial moraine), sub-debris melt as it varies with debris thickness, and ice cliff backwasting uniformly across the medial moraines (Figs. 5-7). These estimates represent the period from 18 June to 16 August 2011.

In order to extrapolate our in situ measurements across the study area we divide the summer specific mass balance $\dot{b}_s$ into contributions from sub-debris and ice cliff melt: $\dot{b}_{debris}$ and $\dot{b}_{icecliff}$. The summer specific mass balance $\dot{b}_s$ is divided into contributions from sub-debris and ice cliff melt: $\dot{b}_{debris}$ and $\dot{b}_{icecliff}$ .Each 0.5 m pixel is designated as debris or ice cliff using the *ABT* ice cliff delineation method. We use the *ABT* method because it consistently performs better than the *SED* method (see Results section). For our best-case distributed-melt estimates, weFor the best case we apply a bias correction by adding 20% to the ice cliff area in each elevation band based on the consistent underprediction of ice cliffs. Extreme ice cliff areas are represented with ±20% areas from the bestis most likely case.

We extrapolate debris thickness across the study area by applying the elevation-dependent curve fits to debris-designated pixels. For the five medial moraines in the center of the glacier (labeled 4 -8 in Fig. 4a) in which 69% of debris thickness measurements were made, we apply a sigmoidal curve fit (Fig. 5). Within these five medial moraines, debris thickness h_{debris} varies with elevation *z* according to:

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$$h_{debris}=\frac{a}{\left[1+10^{b(z-c)}\right]}+d \quad , \qquad (3)$$

where *a*, *b*, *c*, and d are fitted parameters derived using Matlab's polyfit function (Table 1). We apply this sigmoidal curve fit because it best matches the pattern of debris thicknesses within these five medial moraines when they are binned in 50 m elevation bands. For other medial moraines with fewer debris thickness measurements we apply linear curve -fits (Fig. S14). For the western most medial moraine (# 9 in Fig. 4aA), which was difficult to access, we apply uniform debris thicknesses based on a few measurements. We test the importance of the debris thickness applied to medial moraine # 9 in the sSupplementary ml materials (section S3.1.2), the importance of this assumed debris thickness is minor and viable debris thicknesses arefit well within the uncertainty scenarios explored. ies explored.

We apply sub-debris melt rates to all debris-designated pixels based on the estimated debris thickness in each pixel. We use the hyper-fit model to relate debris thickness to sub-debris melt (after Anderson and Anderson, 2016; Crump et al., 2017; Anderson et al., 2018). In the model, the relationship between specific-sub-debris melt $\dot{b}_{debris}$ and debris thickness is:

We apply sub-debris melt-debris thickness relationship (or hyper-fit model after Anderson and Anderson, 2016) to all debris-designated pixels. In the model, the relationship between specific sub-debris melt $\dot{b}_{debris}$ and debris thickness is:

$$\dot{b}_{debris}=\dot{b}_{ice}\frac{h_*}{\left(h_{debris}+h_*\right)} \quad , \qquad (4)$$

where $\dot{b}_{ice}$, the bare-ice melt rate measured near the top of the study area, and h_*, the characteristic debris thickness have values of 5.87 cm d^{-1} and 8.17 cm respectively (Fig. 6). Sub-debris melt rates under debris h_* thick will be half the value of the bare-ice melt rate. If ice is assumed to be at 0° C, h_* can be estimated from physical inputs and parameters following:

$$h_* = \frac{k R}{(1-\phi)} \quad , \qquad (5)$$

where *k* and *φ* are the thermal conductivity and porosity of the debris cover and *R* is the thermal resistance of the debris layer. Here we define *R* as:

$$R = \frac{\bar{T}_s}{L \rho_{ice} \dot{b}_{ice}} \quad , \qquad (6)$$

where *L* and ρ_{ice} the latent heat of fusion and density of ice, $\bar{T}_s$ the average debris surface temperature over the period used to estimate h_* and $\dot{b}_{ice}$ in this case is the bare-ice melt rate over the period used to estimate h_*. The hyperbolic fit between debris thickness and sub-debris melt assumes that energy is transferred through the debris by conduction. While these debris parameters can be measured, in practice they are difficult to measure across debris-covered glaciers so we use an empirical fit to debris thickness-melt data to constrain h_*.

We apply a uniform~~the~~ ice cliff backwasting rate~~-elevation relationship~~ to all ice cliff-designated pixels. We ignore ice cliff backwasting variation with orientation, as there is no clear relationship between backwasting rate and orientation in our measurements (Fig. 7). We did not find a consistent difference between backwasting for ice cliffs with and without ponds at their base (Fig. 7) and no clear relationship between backwasting rate and medial moraine is apparent either (Fig. S8~~Supplementary material~~). We apply the mean specific horizontal ice cliff retreat across the study area:

$$\dot{b}_{backwasting} = f \quad , \quad (7)$$

where *f* is the mean backwasting rate 7.1 cm d^{-1} (an elevation-dependent pattern is explored in section S3.1.3~~the supplementary material~~). Because ~~the~~ backwasting rates are ~~is~~ measured horizontally, we apply an average dip relative to the horizontal plane (*θ*) to estimat~~t~~e the melt perpendicular to ~~the~~ ice cliff surfaces:

$$\dot{b}_{icecliff} = \dot{b}_{backwasting} \cos(90^\circ - \theta) \quad (8)$$

In the best case we assume a uniform ice cliff slope (*θ*) for all ice cliffs of 48° based on the mean of slope measurements made at the top of each of the 60 ice cliffs where backwasting rates were measured ~~in the study area~~ (following Han et al., 2010). The mean of average ice cliff slopes from 6 other glaciers is 49° (section S1.3~~Supplemental materials~~). Including the mean slope estimate from this study, the standard deviation of mean ice cliff slopes is 5°, which we use for our uncertainty estimates.

In order to estimate melt rates ~~the mass balance~~ with elevation we integrate the contributions of ice cliff and sub-debris ablation across 2~~5~~0 meter elevation bands:

$$\bar{b}^i = \frac{\iint^{A^i_{debris}} \dot{b}_{debris}\, dx\, dy + \iint^{A^i_{icecliff}} \dot{b}_{icecliff}\, dx\, dy}{A^i} \quad (9)$$

where $\bar{b}^i$ is the mean ablation rate within the elevation band *i* in units of m d^{-1}, A^i_{debris} is the total debris-covered area, corrected for the surface slope of each debris-covered pixel using the 2013 WV-derived DEM discussed above, within the elevation band, $A^i_{icecliff}$ is the total ice cliff area, correcting for the slope of each ice cliff pixel based on the assumed ice cliff slope, within the elevation band, A^i is the total planview area within the elevation band ,and *dx* and *dy* are both 0.5 m the original resolution of the WV imagery used for ice cliff delineation.

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2.3.1 Uncertainty of distributed melt rates

We present one best-distributed melt rate estimate, which we bound with two extreme cases. These bounds are based on the compounding uncertainty of parameter choices meant to tilt the estimates in the direction of reduced or increased melt, this allows us to test the plausibility of ice cliffs leading to maximum melt within the zone of maximum thinning. In the extreme cases for the debris thickness, curve fits were made through the 25% and 75% data points in each elevation bin. We use the interquartile range because the debris thickness within each elevation band is skewed towards values closer to 0, such that a normal distribution is not applicable (Fig. 5; section S3.1). We also apply ±1 st. dev. range for sub-debris melt and ice cliff backwasting rates, and a ±1 st. dev. range for ice cliff slopes. Extreme ice cliff coverage was defined by ±20% of the bias corrected coverage within each elevation band. See Table 1 for the extreme parameters used for the distributed melt estimates. With these parameter choices 98.4 % of all simulations lie inside the uncertainty range for combined sub-debris and ice cliff melt.

We present one best distributed empirical melt estimate, which we bound with two extreme cases. These bounds are based on the compounding uncertainty of parameter choices meant to tilt the estimates in the direction of reduced or increased melt, this allows us to test the plausibility of ice cliffs leading to maximum melt within the zone of maximum thinning. For the best case the curve fits through debris thickness is calculated using the median of data from the 50-m elevation bins (Fig. 5). See Table 1 for the extreme parameters used for the distributed melt estimates. In the extreme cases for the debris thickness, curve fits were made through the 25% and 75% data points in each elevation bin. We use the interquartile range because the debris thickness within each elevation band is skewed towards values closer to 0, such that a normal distribution is not applicable (Fig. 5; Supplemental Material). We also apply ±1σ range for sub-debris melt and ice cliff backwasting rates, and a ±1σ range for ice cliffs slopes. Extreme ice cliff coverage was defined by ±20% of the bias corrected coverage within each elevation band. With these parameter choices 98.4 %% of all simulations lie inside the uncertainty range for combined sub-debris and ice cliff melt (Fig. 12).

We alsIn addition to the uncertainty evaluation presented here we also explore fiveour additional uncertainty cases in section S3 of the supplementary materialsthe supplemental materials. There we extrapolate debris thickness down each medial moraine using linear curve fits, using a single sigmoidal debris thickness-elevation relationship across the study area, using a linear relationship between backwasting and elevation, with even more uncertainties for each curve fit (in which the error envelope includes greater than 99.996 % of possibilities), and with different debris thicknesses for the westernmost medial moraine. All explorations produce similar area-averaged melt-elevation relationships.

2.3.2 Bare-ice melt rates extrapolated across the study area

For reference we also estimate the bare-ice melt rate through the study area for the summer of 2011, in the hypothetical case that no debris was present on the glacier. We calculate the bare-ice degree-day factor from several ablation stakes in bare-ice in the northeastern portion of the study area near 700 m a.s.l. We calculate the degree-day factor for ice (e.g., Hock, 2003) using measured bare-ice ablation and air temperatures interpolated onto the glacier (Supplementary material). We use hourly air temperature data from the Gates Glacier and May Creek meteorological stations to estimate the air temperature at each measurement location. Gates Glacier station is located just off the glacier margin at 1240 m a.s.l. and May Creek station is located at an 490 m a.s.l. located 15 km to the southwest of the town McCarthy (Fig. 1).

3 Results

3.1 In situ measurements

Figure 5 shows debris thickness as it varies with elevation. Debris thickness tends to increase downglacier and varies from less than a few millimeters above 700 m a.s.l. to as high as 1 m above an ice cliff at 475 m a.s.l. (Table 2). Debris tends to be thicker in the medial moraines near the glacier margin, especially where ice margin retreat has been small (Fig. 4; Fig. S14). On the east side of the study area, in medial moraine 3, debris greater than 40 cm thick was measured. Debris consistently 1 m thick was observed at 730 m a.s.l. just to the west of the study area in moraine 9. Toward the glacier interior and between 650 and 700 m a.s.l. debris thickness did not exceed 15 cm. While we did not measure debris thickness below 450 m a.s.l., visual inspection from across the proglacial lake suggests that debris exceeded 1 m above some ice cliffs. The mean uncertainty of our debris thickness measurements is ±1.3 cm and the standard deviation is ±1.4 cm (Fig. S4). These errors are negligible compared to the changes in measured debris thickness across the study area (Fig. 5).

Figure 6 shows the relationship between sub-debris melt rate and debris thickness (or Østrem's curve) during the study period (Table 2). Melt rates are highly variable beneath debris less than 3 cm. The mean uncertainty in the sub-debris melt rates is ±0.06 cm d^{-1} and the standard deviation is 0.03 cm d^{-1}. The maximum uncertainty is 0.125 cm d^{-1} and applies to three ablation stakes from which measurements were taken over a short 8 day period. These measurement uncertainties are negligible compared to the changes in melt rate with debris thickness (Fig. 6).

The mean ice cliff backwasting rate is 7.1 cm d^{-1} and the standard deviation for the full population of measured ice cliffs is 2.5 cm d^{-1}. The maximum and minimum measured backwasting rates are 15 and 2.5 cm d^{-1} respectively (Table 2). Figure 7 shows measured backwasting rates as they vary with elevation and aspect. There is no apparent aspect dependence on backwasting rates and ice cliffs backwasted at similar rates with and without ponds or streams at their base (Fig. 7) . The mean backwasting rate uncertainty is ±0.5 cm d^{-1} (Fig. 7; Fig. S8). Maximum estimated uncertainty is ±1 cm d^{-1} for 10 cliffs that were measured over the shortest interval (21 days). The standard deviation of uncertainty is ±0.2 cm d^{-1}.

~~Figure 5 shows debris thickness as it varies with elevation. Debris thickness tends to increase downglacier and varies from less than a few millimeters above 700 m a.s.l. to as high as 1 meter above an ice cliff at 475 m a.s.l. (Table 2). Debris cover tends to be thicker in the medial moraines near the glacier margin, where ice margin retreat has been small (Fig. 4; Supplementary Figure 15). Debris greater than 40 cm thick was measured in medial moraine 3 above 600m a.s.l. And debris consistently 1 m thick was observed just out of the study area but still in moraine 9 at 730 m a.s.l. Toward the glacier interior and between 650 and 700 m a.s.l. debris thickness did not exceed 15 cm.~~

~~Debris thicknesses on glacier surfaces can vary by meters over 10-meter scales (e.g., Nicholson et al., 2018). Some of the scatter in our debris thickness measurements is derived from debris thickness variability caused by the local transport of debris by surface processes, in addition to the inevitable stochastic delivery from hillslopes above the glacier. 53 % of our debris thickness measurements were derived from the top of ice cliffs. This potentially biases our measurements toward thinner values because surface debris tends to be thicker in topographic lows.~~

~~Figure 6 shows the relationship between sub-debris melt rate and debris thickness (or Østrem's curve) during the study period (Table 2). Highly variable melt rates beneath debris less than 3 cm thick prevented the establishment of a relationship accounting for the melt-increasing effects of thin debris (e.g., Østrem, 1959).~~

~~The mean ice cliff backwasting rate was 7.1 cm d^{-1} and the standard deviation for all measured ice cliffs was 2.5 cm d^{-1}. The maximum and minimum measured backwasting rate were 15 and 2.5 cm d^{-1} respectively (Table 2). Figure 7 shows measured backwasting rates. While there is significant scatter within any elevation band a weak negative relationship between ice cliff backwasting and elevation is apparent (Supplemental Figure 7). Ice cliffs backwasted at rates similar rates with and without ponds and streams at their base and there is no apparent aspect dependence on backwasting rates (Fig. 7) .~~

3.2 Remotely-sensed ice cliff extent

3.2.1 Performance of automatic ice cliff delineation methods

The adaptive binary threshold (*ABT*) method outperforms the Sobel edge delineation (*SED*) method. Averaged across the validation dataset, the *ABT* method correctly identifies 58% of ice cliff area, with 21% false positives. Percentages are relative to the hand-delineated validation dataset. The *SED* method yields a lower percentage of correctly identified ice cliffs (45%), but also produces fewer false positives (14%). In regions where we do not have manually digitized ice cliffs, our estimates of ice cliff area represent both true and false positives. Assuming our success rate is consistent across the glacier, we expect the *ABT* and *SED* approaches to detect 79% and 69% of the true ice cliff area, respectively.

Some systematic errors are evident, as anomalously light and dark regions of the glacier produce higher error. Regions of thin debris are especially problematic when using the *SED* method (Fig. 9; see also Herreid and Pellicciotti, 2018). To correct for this error in the *SED* results, where debris is very thin, we manually removed areas with highly erroneous ice cliff delineations; these only occur at higher elevations in the study area (Fig. 9). Due to its poorer performance, we do not use the *SED*-defined ice cliff area for ~~the~~ distributed melt rate~~ass balance~~ estimates.

3.2.2 Spatial distribution of ice cliffs

The two delineation methods produce broadly similar ice cliff distributions. The *SED* method, specifically, overestimates ice cliff area at high elevation due to the thin, dark-colored debris. Over the 24.2 km^2 study area, we estimate that ice cliffs cover 2.14 km^2 (8.8%) and 2.32 km^2 (9.7%) of ice cliff planview area using the *SED* and *ABT* methods, respectively (Fig. 10). We normalized ice cliff area by glacierized area within each elevation band, which we refer to as ice cliff fractional area or coverage. If we apply a bias correction to the *SED* (31%) and *ABT* (21%) estimates based upon under-delineation rates in manually digitized areas, the ice cliffs cover 11.4% and 11.7% of the glacier respectively.

In total, 11.7 % of the debris-covered tongue of Kennicott glacier is occupied by ice cliffs (see Anderson (2014) for an independent but still consistent estimate of ice cliff coverage). Focusing on the *ABT* results, which provide the most accurate estimate, we find a "humped" profile in the elevational distribution of ice cliff area (Fig. 10). Ice cliff fractional area is relatively uniform at 7-8% except for a broad peak between 500-660 m a.s.l. within which fractional area reaches 13% between 540 and 560 m.

The two delineation methods produce broadly similar ice cliff distributions. The *SED* method, specifically, overestimates ice cliff area at high elevation due to the thin, dark-colored debris. Over the 24.2 km^2 debris-covered portion of the study area, we estimate that ice cliffs cover 2.14 km^2 (8.8%) and 2.32 km^2 (9.7%) of ice cliff planview area using the *SED* and *ABT* methods, respectively (Fig. 10). If we apply a bias correction to the *SED* (31%) and *ABT* (21%) estimates based upon under-delineation rates in manually digitized areas, the ice cliffs cover 11.4% and 11.7% of the glacier respectively. Focusing on the *ABT* results, which provide the most accurate estimate, we find a "humped" profile in the elevational distribution of ice cliff fractional area. Ice cliff fractional area peaks between 520 and 620 m a.s.l. Below this elevation, ice cliff area decreases (Fig. 10).

In total, 11.7 % of the debris-covered tongue of Kennicott glacier is occupied by ice cliffs. See Anderson (2014) for an estimate using an independent method on Kennicott Glacier that is consistent. 11.7 % is 60% more coverage by percentage than on the Changri Nup Glacier, the glacier with the second highest coverage of ice cliffs studied to date (Table 4). The Kennicott Glacier has the lowest mean debris thickness (13 cm) of glaciers with reported ice cliff coverage percentages and supports, by far the highest percentage of ice cliffs. This implies that ice cliff coverage could vary with debris thickness or a variable that co-varies with debris thickness (Table 4).

We normalized ice cliff area by glacierized area within each elevation band, which we refer to as ice cliff fractional area. Ice cliff fractional area is relatively uniform at 7-8% except for a broad peak between 500-660 m a.s.l. within which fractional area reaches 13% at 540-560 m. The lower edge of this peak overlaps with the upper end of the *ZMT*.

3.3 Distributed estimates of melt

In Figure 11, we show the best distributed melt estimate split into sub-debris and ice cliff contributions across the study area. When averaged across the entire study area, 74% of melt is derived from sub-debris melt and 26 (with extreme bounds of 20 , 40) % from ice cliff melt.

Figure 12 shows that the insulating effect of debris is more important in setting the area-averaged melt rate than ice cliffs, especially where debris is thinner. Modeled bare ice melt rates, which are meant to represent the hypothetical melt rate if debris were absent from the study area, increase towards lower elevations and range from 5.9 to 7 cm d^{-1}. Decreasing sub-debris melt downglacier, due to thickening debris, results in a deviation from the bare-ice melt rate below 700 m a.s.l. Area-averaged sub-debris melt rates decline from 4.2 cm d^{-1} (3.2, 5.1) at the top of the study area to 1.6 cm d^{-1} (0.98, 2.0) near the terminus.

Figure 11 we show the best distributed estimate of melt split into sub-debris and ice cliff contributions across the study area. While sub-debris melt decreases toward the terminus due to thickening debris, we apply uniform ice cliff backwasting rates with the debris-covered portion of the study area.

When averaged across the entire study area, 8% of melt is derived from sub-debris melt and 26 (20 , 40)% from ice cliff melt. Figure 12 shows that the insulating effects of debris cover is more important in setting the area-averaged melt rate than ice cliffs, especially where debris is typically thinner at higher elevations. Modeled bare ice melt rates, which are meant to represent the hypothetical melt rate if debris were absent from the study area, increase towards lower elevations and range from 5.9 to 7 cm d^{-1} (Fig. 12). The dominance of decreasing sub-debris melt downglacier, due to thickening debris, results in a deviation from the bare-ice melt rate above 700 m a.s.l. (relative to the 2013 glacier surface). Elevation-band averaged sub-debris melt rates decline from 4.2 cm d^{-1} (3.2, 5.1) at the top of the study area to 1.6 cm d^{-1} (0.98, 2.0) near the terminus.

Ice cliffs, when their total melt contribution is averaged over the e~~entire e~~levation bands, produce~~d~~ rates of 0.73 cm d^{-1} (0.31, 1.29) at the top of the study area and 0.69 cm d^{-1} (0.33, 1.4) near the terminus. The maximum contribution of ice cliffs to area~~band~~-averaged melt occurs at 510~~near 500~~ m and has a value of 1.3 cm d^{-1} (0.58, 2.4), ~~. Ice cliffs contribute most to mass loss in the 500 to 520 m a.s.l. elevation band,~~ close to where the ice cliff fractional area also maximizes. Ice cliffs between 500 and 520 m a.s.l. generate the highest percentage (42% (34, 58%)) of the total melt~~ass loss~~ due to ice cliffs and sub-debris melt within the study area.

4 Discussion

We discuss the implications of our in situ mass balance measurements, our new automatic ice cliff delineation method, and finally the implications of our distributed melt estimates as they relate to the zone of maximum thinning.

4.1 In situ~~Field~~ measurements

4.1.1 Sub-debris melt rates

Our measured sub-debris melt rates are highly variable beneath debris less than 3 cm (Fig. 5). It appears that local meteorology and/or surface hydrology are important controls on the melt-increasing effect of thin debris (see Mihalcea et al., 2006; Reid and Brock, 2010 for similar observations). Our sub-debris melt rates support the observations of Fyffe et al. (2020): there is no consistent melt enhancement under debris less than 3 cm. Debris typically forms parabolic-shaped medial moraines in cross section (e.g., Anderson, 2000) suggesting that the melt-reducing effect of debris dominates, in the study area (and upglacier as well). Despite the scatter of melt rates under thin debris, the question remains: Under what conditions does thin debris increase area-averaged melt rates relative to adjacent bare-ice melt rates?

~~Our ablation stake derived sub-debris melt rates are highly variable beneath debris less than 3 cm (Fig. 5). It appears that local environmental conditions are as important as the potential for melt enhancement due to thin debris (see Mihalcea et al., 2006; Reid and Brock, 2010 for similar observations). Our measured sub-debris melt rates are consistent with the observations made by Fyffe et al. (2020): a consistent melt enhancing effect due to debris less than 3 cm is not apparent. Debris typically forms parabolic-shaped medial moraines in cross-section (e.g., Anderson, 2000) suggesting that the melt-suppressing effect of debris dominates, in the study area (and upglacier as well). Despite this the melt enhancing effect of debris less than 3 cm remains an important potential melt-enhancing effect of debris cover, that is most likely to increase surface melt at the upglacier end of debris covers.~~

Based on our debris thickness and~~to~~ sub-debris melt measurements, the characteristic debris thickness (h_*) was 8.17 cm. ~~Practically an h_* of 8.17 cm means that sub-debris melt rate will be 50% of the bare ice melt rate at 8.17 cm debris thickness (Eqn. 4).~~ The relationship between melt rate and debris thickness from Kennicott Glacier is similar to those derived from other debris-covered glaciers at similar latitudes (Fig. S6~~des (Supplemental Material~~). Th~~e~~e consistent decline in sub-debris melt rates~~s~~ as debris thickens is not expected considering that the global mean value of h_* is 6.6 ± 2.9 cm (1 standard deviation; Anderson and Anderson, 2016).~~σ)(based on 15 glaciers from Anderson and Anderson, 2014).~~

4.1.2 Ice cliff backwasting rates

The backwasting rates presented here are the first, that the authors are aware of, published from a debris-covered glacier outside of Eurasia. Despite filling a new geographical niche, the average backwasting rates from Kennicott Glacier are similar to those from high-altitude Eurasian glaciers at lower latitudes with thicker debris cover (Table 3). The similarity in backwasting rates suggests that there are compensating effects between altitude, latitude, and day length. These backwasting rate data are important for validating future regional and global mass balance estimates incorporating the effects of debris cover and ice cliffs.

Backwasting rate measurements were taken from 60 ice cliffs that varied with elevation, orientation, adjacent debris thickness, debris composition, and connection with ponds and streams (Figs. 7, S8). It is logical to expect that backwasting rates would be higher at lower elevations where more energy is available for melt (e.g., Brock et al., 2010), but significant scatter limits the clear establishment of a causal relationship with elevation, noting that a weak increase in backwasting rate is apparent towards low elevation when data are binned in 50 m elevation bands (Fig. S7). Measured backwasting rates do not consistently vary with orientation (Fig. 7). This observation contrasts with observations from lower latitude debris-covered glaciers (Sakai et al., 2002; Buri and Pellicciotti, 2018), suggesting that there may be a latitudinal control on backwasting rates as they vary with orientation. Noting the small sample size, we also found that undercutting ponds (n=4) and streams (n=8) at the base of ice cliffs did not consistently increase backwasting rates (Fig. 7), though ponds may allow for the long-term persistence of ice cliffs (e.g., Brun et al., 2016; Miles et al., 2016). The scatter in our backwasting rate measurements precludes a clear establishment of cause and effect. The scatter is likely at least partially related to local topography and shading (Steiner et al., 2015), a control we do not explicitly consider here. Further field efforts with an even larger population of ice cliffs would allow for statistical analyses that reveal spatial controls on ice cliff backwasting rate.

We take an in situ measurement-based approach to quantify ice cliff backwasting rates. We assume that single measurements taken from the top of 60 ice cliffs represent the mean backwasting rate across the thousands of ice cliffs on Kennicott Glacier. It is tempting to turn towards process-based models of ice cliff backwasting rates, but modeling complicated processes necessitates a large number of free parameters. Most model parameters vary in unknown ways across debris-covered glacier surfaces. The best way to reduce parameter uncertainty and validate model results is to simply make more in situ measurements. Whether you model ice cliff backwasting or follow a more empirical approach as we have here, the validity of the conclusions rests on the number and quality of measurements.

4.2 Remotely-sensed ice cliff extent

4.2.1 Automatic ice cliff delineation methods

The Adaptive Binary Threshold (*ABT*) method provides an especially accurate estimate of ice cliff area as it varies across a large debris-covered area. Both the *ABT* and *SED* ice cliff delineation methods underpredict ice cliff area somewhat. These methods require that ice cliffs are dark relative to surrounding debris cover, which is generally true for Kennicott and several other debris-covered glaciers in the Himalaya we examined. Ice cliffs may be brighter than the surrounding debris if the ice cliffs are not covered with thin debris films or if they are strongly illuminated. The *ABT* method will therefore tend underpredict south-facing ice cliffs, although we observe many correct delineations.

The *ABT* method is a promising new approach for the large-scale delineation of ice cliffs. Because of the high accuracy of the method, its transferability to other glaciers should be tested using the parameters already tuned in this study and with new parameters tuned for other glaciers. Future improvements to the *ABT* method could be made by using more advanced image segmentation techniques (e.g., Leyk and Boesch, 2010), by utilizing image texture analysis, or by allowing image processing parameters to adaptively vary across the glacier. Using multispectral imagery would also likely improve delineation, although such imagery is less readily available.

4.2.2 Spatial distribution of ice cliffs

The 11.7 % ice cliff coverage in the debris-covered tongue of Kennicott Glacier is the highest coverage from any glacier studied to date. The 11.7% coverage is 60% more coverage by percentage than the debris-covered portion of Changri Nup Glacier, the glacier with the second highest ice cliff coverage (Brun et al., 2018; Table 4). The debris-covered portion of Changri Nup Glacier is also considerably smaller in area (1.5 km^2) than the debris-covered tongue of Kennicott Glacier (24.2 km^2). Kennicott Glacier has the lowest mean debris thickness (13.7 cm) of glaciers with reported ice cliff coverage percentages and supports, by far the highest percentage of ice cliffs. This implies that ice cliff coverage could vary with debris thickness or a variable that co-varies with debris thickness (e.g., debris mobility; Moore, 2018).

4.3 Distributed melt estimates

Our distributed melt rate estimates include potential slight biases from our in situ measurements towards higher melt rates. 53 % of our debris thickness measurements were derived from the top of ice cliffs and topographic highs. Because debris tends to concentrate in topographic lows our debris thickness measurements may be biased toward thinner debris and higher melt. Our measured ice cliff backwasting rates are based on repeated measurements at a single location at the top of each ice cliff. Maximum backwasting rates across each ice cliff are more likely to occur near the top (Buri et al., 2016b; modeled from Lirung Glacier, Nepal). Applying our measurements across single ice cliffs or the entire ice cliff population may therefore also overestimate ice cliff melt.

On Kennicott Glacier, ice cliffs most likely contribute 26% (with extreme bounds of 20 and 40%) of melt in the study area (Table 4). For glaciers with mean debris thicknesses larger than 50 cm, where sub-debris melt rates are low, ice cliff relative contributions are larger than 26% and as high as 40%, despite having much lower ice cliff fractional coverage than Kennicott Glacier. This relationship holds when comparing individual debris-covered glaciers (Table 4) and as debris thickness increases downglacier on Kennicott Glacier (Fig. 12b). Ice cliffs are *relatively* more important for mass loss the thicker the debris cover (Table 4).

The debris-covered tongue of Kennicott Glacier provides an opportunity to test the importance of ice cliffs on debris-covered glacier mass balance. The thin debris leads to melt rates closer to bare-ice melt rates than most other studied debris-covered glaciers. Ice cliff backwasting rates are comparable or higher than rates from other glaciers (Table 3). Kennicott Glacier also has the highest fractional coverage of ice cliffs, relative to other studied glaciers, which also serves to increase melt rates (Table 4). Despite this, ice cliffs on Kennicott Glacier do not compensate for the *absolute* melt-reducing effects of debris. Area-averaged melt rates, including ice cliff contributions through the study area, are lower than hypothetical bare-ice melt rates at the same elevation (Fig. 12a). Ice cliffs are therefore unlikely to counter the melt-reducing effects of debris on glaciers with thicker debris and/or lower ice cliff coverage.

The analysis above leads to the expectation that *absolute* area-averaged rates on debris-covered glaciers will tend to decline downglacier as debris thickens, an inference, that is further supported by Bisset et al. (2020)'s analysis from selected glaciers across High Mountain Asia. Future efforts to represent the effect of ice cliffs on debris-covered glacier mass balance should consider using a modified debris thickness-melt relationship with a percentage melt enhancement based on remotely-sensed ice cliff coverage and empirical relationships like those developed in this study.

4.3.1 Sensitivity test: *Do ice cliffs maximize melt in the zone of maximum thinning (ZMT)?*

We explore what hypothetical perturbations would be needed to produce the highest glacier-wide melt rates where the glacier has thinned the most. During the study period (mid-June and mid-August of 2011), the melt within the zone of maximum thinning (*ZMT*) was strongly reduced by debris cover, based on our best estimate. We assume that the *ZMT* – which was stable from 1957 to 2004 and 2000 to 2007– remained in the same location during the summer of 2011. The *ZMT* was debris covered from at least 1957 to the present (Fig. S21). Ultimately, this sensitivity analysis shows how extreme the parameter choices would need to be to maximize melt in the *ZMT*.

Debris cover and sub-debris melt: Debris thickness would have to decrease, specifically in the *ZMT*, from ~20 cm to 2 cm to produce maximum glacier-wide melt rates there. For melt to be maximized in the *ZMT*, where debris is ~20 cm thick, sub-debris melt rates would have to increase from ~ 1.6 cm d^{-1} by a factor of three to 4.8 cm d^{-1}. Our distributed melt-estimation approach assumes that small-scale debris thickness variability has a negligible effect on area-averaged melt rates, despite the non-linear debris-melt rate relationship (Fig. 6). The sensitivity test in this paragraph reveals how improbable it is for small-scale debris variability to lead to maximum melt rates in the *ZMT* (see section S3).

Ice Cliffs (and other melt hotspots): In order for ice cliffs to increase melt and produce maximum glacier-wide melt rates in the *ZMT*, *absolute* backwasting rates would need to be 6.5 times higher than those measured in the summer of 2011. The hypothetical backwasting rates required to maximize melt in the *ZMT* are unrealistic; a compilation of previously published backwasting rates in Table 3 supports this. We implicitly assume that the peak melt season (mid-June to mid-August) is a good proxy for annual-average ablation rates. It is unlikely that this assumption affects our conclusions. In order for *absolute* annual area-averaged ablation rates to be maximized in the *ZMT*, ice cliff backwasting rates in shoulder seasons, specifically in the *ZMT*, would need to be 6.5 times those measured in the summer of 2011. These conditions would need to persist for at least 2 months outside of the peak melt season and despite reduced availability of energy for melt in shoulder seasons.

While we do not explicitly document the melt rate of ponds and streams we follow Kraaijenbrink et al. (2017)'s approach and assume that all melt hotspots melt at the same rate as ice cliffs. Using this assumption, in order for melt hotspots to compensate for the melt-reducing effects of debris in the *ZMT*, melt hotspots would need to cover 90% of the glacier surface, specifically in the *ZMT*. This assuredly is not the case.

4.4 Importance of upglacier melt and ice flow

To consider what controls the *ZMT* we return to the continuity equation for ice (Eq. 1). If we fail to account for the movement of ice, then local surface mass balance is the only factor that can cause ice thickness change, and the continuity equation reduces to:

$$\frac{dH}{dt}(x) = \dot{b}(x) - \nabla \cdot Q(x) = \dot{b}(x) - 0 \quad . \quad (10)$$

If this equation were valid across Kennicott Glacier, then the zone of maximum thinning would align with the region of maximum area-averaged surface melt rates. However, melt is not maximized in the *ZMT* (Fig. 12). Previous studies have shown that ice is in motion in and above the *ZMT* (Armstrong et al., 2016, 2017). Eq. 10 therefore cannot be applied to explain the location of the *ZMT* for Kennicott Glacier. The movement of ice (i.e., *ice dynamics*) down valley must play a role.

We now consider the scenario in which increased melt upglacier from the *ZMT* has led to dynamic thinning in the *ZMT* (also see Nye, 1960; Vincent et al., 2016). It is feasible that upglacier from the *ZMT* increased melt rates have reduced ice thicknesses through time, which in turn led to a reduction in ice speeds. Thinner ice and lower speeds upglacier from the *ZMT* reduce the volume of ice delivered per time (*Q*, ice discharge) to the *ZMT*. This scenario results in a downglacier gradient of ice discharge, *dQ/dx*, that closer to zero across the *ZMT*. A *dQ/dx* declining towards zero through time would in turn lower the ice emergence causing rapid surface lowering and thinning in the *ZMT*.
Significant scatter is present in the ice cliff backwasting rates as they vary with elevation, suggesting that controls independent of elevation are important. But when our backwasting rate data are binned in 50 m elevation bands a weak increase in backwasting rates towards lower elevations is apparent. Potential causes of higher backwasting rates at lower elevations are: 1) increased air temperatures. Increased debris thickness leads to higher debris surface temperatures, longwave fluxes, and energy available for melt (e.g., Brock et al., 2010); or 2) increased debris veneers and lower ice cliff albedo at low elevations (e.g., Reid and Brock, 2014). Because ice cliffs, by definition persist above the angle of repose, large clasts (pebble-sized and larger) tend to trundle to the base of ice cliffs. But fine materials (clay and sand sized particles) on the other hand are more likely to persist on steep ice cliff surfaces. This could be due to local surface roughness on the ice cliff allowing for fine material to accumulate. For finer grains attractive inter particle surface forces, frictional interlocking of grain aggregates, and electrochemical forces are more likely to adhere debris to cliff surfaces (e.g., Jain and Kothyari, 2009; Supplementary Photos 1-3). When melt is occurring on the ice cliff, the adhesive and cohesive properties of liquid water may also also help retain fine debris on cliff surfaces. It follows that fine debris will be more likely to decrease ice cliff albedo where debris cover above ice cliffs are composed of more fine material. It has been noted in several studies of debris cover grain size that the percentage of fine material composing debris covers tends to increase towards glacier termini (Owen et al., 2003; Kellerer-Pirklbauer, 2008).

To advance our understanding of why rapid thinning occurs under melt-reducing debris cover we must consider both terms in the continuity equation for ice (Eq. 1) and how they affect one another. We must also expand our perspective and consider the entirety of glaciers, including the debris-free portions upglacier from the debris cover.

Thicker debris cover leads to higher debris surface temperatures, and higher longwave radiation fluxes received by ice cliffs. Despite this physical relationship, the backwasting rates measured on Kennicott Glacier are similar to those measured on glaciers with thicker debris cover and at lower latitude (Table 3). The similarity in backwasting rates suggests that there may be compensating effects between latitude, day length, and altitude. i.e., Himalayan glaciers are present at a lower latitude but they also tend to persist at high elevations compared to, for example, Kennicott Glacier which persists at a much higher latitude but also lower elevation. Ultimately the lack of aspect control on backwasting rates on Kennicott Glacier contrasts with observations from lower latitudes (e.g., Buri and Pellicciotti, 2018), suggesting that there may be a latitudinal control on ice cliff backwasting rates as they vary with orientation.

In this study, backwasting was measured at the top of ice cliffs. Based on the modeling of Buri et al. (2016b) from Lirung Glacier, Nepal (28° N), the highest backwasting rates tend to occur near the top of ice cliffs (noting that only northwest and northeast facing ice cliffs were modeled). But making in situ measurements across a representative population of ice cliffs is very difficult. We assume that a single measurement from 60 ice cliffs would better represent the mean backwasting rate across the thousands of ice cliffs in the study area. The validity of this assumption should be explored in future field campaigns. If it is true that ice cliff backwasting is maximized at the top of ice cliffs then distributed estimates of surface melt using our backwasting rates could overestimate ice cliff backwasting when averaged across entire cliffs. It could be that our ice cliff backwasting rates overestimate the melt potentially skewing our estimates towards higher than actual melt rates in the zone of maximum thinning.

4.2 Ice cliff delineation methods

Our automated methods provide an accurate estimate of ice cliff area, though both the *ABT* and *SED* ice cliff delineation methods underpredict ice cliff area, without bias corrections. These methods require that ice cliffs are dark relative to surrounding debris cover. This observation of darker ice cliffs is generally true for Kennicott and several other debris covered glaciers we examined, but this relationship should be verified before application different glaciers. Output should simply be examined to ensure that such conditions do not contaminate results. Ice cliffs may be brighter than the surrounding debris if the ice cliffs are not covered with thin debris films or if they are strongly illuminated. Our method will therefore likely underpredict south-facing ice cliffs, although we observe many correct delineations.

Future improvements to these delineation methods may be achieved using more advanced image segmentation techniques (e.g., Leyk and Boesch, 2010), by utilizing image texture analysis, or by adaptively changing image processing parameters within a window moving across the image and mosaicing the results. The transferability of optimal processing parameters (both across time and space) requires further investigation, but none-the-less we present a promising approach for the large-scale delineation of ice cliffs. Using multispectral imagery would also likely improve delineation, although such imagery is less readily available. The delineation methods presented here could be compared to the cliff delineation algorithm of Herreid and Pellicciotti (2018) using existing high-resolution DEMs on Kennicott Glacier.

4.3 Distributed estimates of melt

On Kennicott Glacier, ice cliffs most likely contribute 26% (with extreme bounds of 20 and 40%) of melt of the debris-covered tongue. This percentage is more than twice the percentages reported from other glaciers with mean debris thicknesses less than 50 cm (Table 4). This is likely due to the high fractional coverage of ice cliffs on the Kennicott Glacier. For glaciers with mean debris thicknesses much larger than 50 cm, ice cliff contributions are larger than 26% and are as high as 40%. For these other glaciers high ice cliff contributions occur despite much lower ice cliff coverage compared to Kennicott Glacier (Table 4). It follows that relative ice cliff contribution will be higher where sub-debris melt rates are low.

Ice cliffs tend to contribute a higher fraction of mass loss as debris thickness increases. This trend is visible on Kennicott Glacier as debris thickens toward the terminus (Fig. 12). This relationship also appears to hold when considering debris-covered glaciers from different regions (Table 4). As debris thickens the contribution of ice cliff melt also tends to increase. This appears to occur even though the fractional coverage of ice cliffs tends to decrease as mean debris thicknesses increase.

Ice cliffs do not counteract the insulating effects of debris on Kennicott Glacier (Fig. 12). The thin debris within the study area leads to melt rates closer to bare-ice melt rates than most other studied debris-covered glaciers. Measured ice cliff backwasting rates are comparable or higher than measurements from other studies (Table 3. Kennicott Glacier also has the highest fractional coverage of ice cliffs, relative to other studied glaciers, which also serves to increase melt rates (Table 4). Despite this, ice cliffs on Kennicott Glacier do not compensate for the insulating effects of debris. This suggests that the presence of ice cliffs is unlikely to counter the insulating effects of debris on glaciers with thicker debris and/or lower ice cliff coverage.

4.3.1 *Do ice cliffs maximize melt in the ZMT in the summer of 2011?*

During the measurement period between mid June and mid August of 2011, the melt within the zone of maximum thinning (*ZMT*) is strongly suppressed by insulating debris cover. For this discussion we make the assumption that the *ZMT* -- which was stable between the 1957 to 2004 and 2000 to 2007 time periods-- remained in the same location during summer of 2011. Note that from 1957 to present the *ZMT* of Kennicott Glacier has been debris covered (Supplemental Figure 26). All explored debris thickness extrapolation approaches presented here show that the melt profile is strongly suppressed by thick debris, a pattern that remains consistent even when extreme parameters are chosen to increase the melt rate of ice cliffs (Supplemental Material). All of these estimates also include the potential slight biases of our measurements towards 1) thinner debris, and 2) high backwasting rates. We further assess what changes in debris thickness, sub-debris melt rate, ice cliff coverage, or backwasting rates would be required to produce the highest glacier-wide melt rates within the *ZMT*. The point of this exercise is to show how extreme the parameter choices would be to maximize melt within the *ZMT*.

Debris cover and sub-debris melt: Debris thickness would have to decrease, specifically in the *ZMT,* from ~20 cm to 2 cm (a reduction factor of 0.1) to produce maximum glacier-wide melt rates there. 53 % of our debris thickness measurements were derived from the top of ice cliffs and topographic highs. Because debris tends to concentrate in topographic lows our debris thickness measurements may be biased toward thinner debris, making the required reduction in debris thickness even more extreme. Melt would also be maximized in the zone of maximum thinning, where measured debris is ~20 cm thick, sub-debris melt rates would have to increase from ~ 1.6 cm d^{-1} by a factor of 3 to 4.8 cm d^{-1}.

Ice Cliffs: In order for ice cliffs, in the *ZMT*, to enhance melt and produce maximum glacier-wide melt rates in the *ZMT*, backwasting rates would need to be 6.5 times higher than those measured in the summer of 2011. Our backwasting estimates are based on repeated measurements at a single location at the top of each ice cliff. Maximum backwasting rates across each ice cliff are more likely to occur near the top (Buri et al., 2016). Applying our measurements across single ice cliffs or the entire ice cliff population may therefore overestimate ice cliff melt. The hypothetical backwasting rates required to maximize melt in the *ZMT* are therefore unreasonable; a compilation of previously published backwasting rates in Table 3 support this.

~~In order for ice cliffs in the *ZMT* to compensate for the insulating effects of debris and enhance melt in the *ZMT* beyond bare ice melt rates, ice cliff area would need to increase from 11.7% to 90% of the glacier surface. This again suggests that ice cliff melt does not control the location of the *ZMT* at least during the summer of 2011.~~

~~4.4 Østrem's curve expressed in the mass balance profile~~

~~On debris-covered glacier termini, debris tends to thicken towards debris-covered glacier termini (e.g., Anderson and Anderson, 2018) as is the case for Kennicott Glacier. This leads to the expectation that sub-debris melt rates will decline towards the terminus reversing the mass balance gradient, similar to the results and conclusions for glaciers in the Khumbu of Nepal (Bisset et al., 2020). The overall mass balance profile for the summer of 2011 (Fig. 12) shows this Østrem's curve like pattern, suggesting that it is more strongly influenced by debris thickness than melt hotspots. Future efforts to represent the effects of ice cliffs on glacier mass balance at the regional scale could consider using a modified debris thickness-melt relationship with a percentage enhancement based on empirical relationships between debris thickness and ice cliff melt contribution. Even where ice cliffs contribute 42 % of melt the surface mass balance pattern still largely follows Østrem's curve.~~

5 Conclusions

Using novel methods, the spatial distribution of melt rate on a debris-covered tongue in Alaska has been quantified for the first time. We collected abundant in situ measurements on Kennicott Glacier allowing for the extrapolation of debris thickness, sub-debris melt rates, and ice cliff backwasting rates across the 24.2 km^2 study area. Debris thicknesses are extrapolated down flow units, as defined by medial moraines.

A newly developed automatic ice cliff delineation method is the first-of-its-kind to use only high-resolution-satellite imagery. The Adaptive Binary Threshold (*ABT*) method robustly estimates ice cliff coverage for a particularly difficult test case (Kennicott Glacier) in which ice cliffs are abundant and often small. The method performs well even as debris color varies across nine medial moraines. With further testing the *ABT* method could be applied efficiently across numerous glaciers.

Kennicott Glacier is the largest debris-covered glacier for which distributed melt has been rigorously quantified. Kennicott Glacier also exhibits the highest fractional coverage of ice cliffs documented on a debris-covered glacier (11.7%), yet ice cliffs contribute only modestly to the average melt rate across the glacier tongue (26%). Ice cliffs contribute a larger percentage of melt in areas where debris cover is thick, mirroring results from other studied glaciers in Eurasia. Despite this increasing *relative* importance of ice cliffs as debris thickens (Fig. 12b), the area-averaged *absolute* melt rates –that actually control glacier thinning and meltwater production– decline towards the terminus (Fig. 12a). While ice cliffs should not be neglected, our analysis suggests that increased attention be given to debris cover and how it varies across individual glaciers and regions.

The debris-covered tongue of Kennicott Glacier provides an opportunity to test the importance of melt hotspots on debris-covered glacier mass balance and thinning. Thin debris, high ice cliff backwasting rates, and abundant ice cliffs all compound to increase the likelihood that glacier-wide melt rates peak within the debris-covered tongue of Kennicott Glacier. The zone of glacier-wide maximum thinning (*ZMT*) is in a debris-covered, stable location upglacier from the terminus. However, even with extreme uncertainty scenarios, melt rates neither match hypothetical bare-ice melt rates nor result in glacier-wide maximum melt rates in the *ZMT*. We conclude that the reduction of ice discharge from upglacier is necessary to explain the rapid glacier thinning occurring beneath thick debris at Kennicott Glacier.

~~The melt within a debris-covered tongue of a large Alaskan Glacier has been quantified. We conclude that:~~

- ~~For Kennicott Glacier the zone of glacier-wide maximum thinning occurs under melt-reducing debris cover, up-glacier from its terminus. Based on the periods 1957-2004 and 2000-2007 the zone of maximum thinning appears to be in a stable location (Das et al., 2014) and has been continuously debris covered since at least 1957.~~
- ~~Kennicott Glacier is covered by thinner debris than most previously studied glaciers (mean debris thickness of ~14 cm). Debris thickness tends to increase down glacier. It is thickest near the terminus near the margin of Kennicott Glacier.~~
- ~~We see significant scatter in melt rates for debris under 3 cm thick. In some locations melt is amplified relative to bare ice melt rates and in others melt is suppressed, suggesting that local glacier surface hydrology or meteorology may be important in determining whether or not melt amplification occurs under debris less than 3 cm thick.~~

- ~~Measured ice cliff backwasting rates from Kennicott Glacier are as high as those measured from any other glacier measured to date. We find no consistent control of backwasting rate by orientation, or whether streams or ponds are present at the base of the ice cliff. More measurements are needed to robustly test these results. A slight dependence of backwasting rate with elevation may be present, although there is considerable variability within any elevation band.~~
- ~~A new ice cliff delineation method is presented using high-resolution panchromatic WorldView1 satellite imagery. This method provides a robust estimate of ice cliff extent for a particularly difficult test case in which ice cliffs are abundant, and often small. The method is robust even as debris surface color varies across 9 medial moraines.~~
- ~~Within its debris-covered tongue, Kennicott Glacier hosts the highest percentage of ice cliffs by area (11.7%) of any previously studied glacier.~~
- ~~Abundant in situ measurements allow extrapolation of debris thickness, sub-debris melt, and ice cliff backwasting, across the study area. Debris thicknesses are extrapolated down individual flow paths.~~
- ~~During the summer of 2011, approximately 26% of melt in the entire debris-covered tongue is attributable to ice cliffs while covering 11.7% of the study area. In the lowest 4 kilometers of Kennicott Glacier where debris tends to be thicker than 15 cm and hence sub-debris melt rates are low, ice cliffs constitute up to 42% of melt.~~
- ~~Ice cliffs strongly contribute to the surface melt of Kennicott glacier. Ice cliffs contribute a larger percentage of mass loss in places where debris cover is thick, a pattern observed across the Kennicott Glacier and for other studied glaciers from other regions.~~
- ~~The mass balance profile within the debris covered portion of the glacier appears to follow the debris-melt relationship or Østrem's curve.~~
- ~~If surface melt was the sole control on the location of the zone of maximum thinning (*ZMT*) then surface melt must peak within the *ZMT*. The thin debris, high ice cliff backwasting rates, and abundant of ice cliffs found on the debris-covered tongue of Kennicott Glacier (relative to previously studied debris-covered glaciers) all suggest that the ice cliffs should compensate for the melt-suppressing effects of debris (relative to bare-ice melt rates). However even with extreme parameter choices and extreme uncertainty scenarios melt rates in the zone of maximum thinning, neither match hypothetical bare-ice melt rates at the same elevation nor result in glacier-wide maximum melt rates within the *ZMT*.~~
- ~~Because melt hotspots do not appear to control the *ZMT* location, during the study period, we suggest that ice dynamics and the decline in ice discharge from upglacier appears to be vital to explain high glacier thinning rates despite thick, melt-insulating debris cover.~~

Data availability

Datasets are openly available at DOI:10.5281/zenodo.4118672
~~Datasets and results are available upon request.~~

Author contribution statement

LSA, WHA, and RSA ~~WHA, and RSA~~ designed the study. LSA composed the manuscript, collected all field data, and completed all analyses besides developing the automatic ice cliff delineation method. WHA developed the ice cliff delineation method, delineated ice cliffs, and wrote the associated text. RSA advised LSA and WHA through the study and contributed to the text and figures. PB contributed to the text and added important discussion that improved the manuscript. All authors aided in composing the manuscript.

Competing Interests

The authors declare that they have no conflict of interest.

Acknowledgements

We thank Francesca Pellicciotti for her considerable efforts editing this manuscript as well as Evan Miles, David Rounce, and two anonymous reviewers whose comments also improved this manuscript. LSA acknowledges support from a 2011 Muire Science and Learning Center Fellowship, NSF DGE-1144083 (GRFP), and funding from the European Research

Council (ERC) under the European Union's Horizon 2020 research and innovation programme under grant agreement No 759639. RSA and WHA acknowledge support of NSF EAR-1239281 (Boulder Creek CZO) and NSF EAR-1123855. WHA acknowledges support from NSF OPP-1821002 and the University of Colorado at Boulder's Earth Lab initiative. We thank Craig Anderson and Emily Longano for invaluable field support. We thank Dirk Scherler, Indrani Das, Regine Hock, Martin Truffer, Jack Holt, Eric Peterson, Brandon Tober, Katy Barnhart, Andy Wickert, and Eric Winchell for thoughtful discussions. LSA thanks the organizers and participants of the 2010 Glaciological Summer School held in McCarthy, Alaska, which inspired this research. We thank Per Jenssen, Susan Fison, Ben Hudson, Patrick Tomco, Rommel Zulueta, the Wrangell-St. Elias Interpretive Rangers, the Wrangell Mountains Center, and Ted Scambos (NSIDC) for logistical support and the gracious loan of equipment. We thank Lucy Tyrell for facilitating outreach efforts. We also thank Joshua Scott, Wrangell-St Elias National Park and the Polar Geospatial Center for access to satellite imagery as well as Etienne Berthier for sharing DEMs. WHA thanks Waleed Abdalati, Mahsa Mousavi, and Stefan Leyk for guidance in image processing.

~~We thank Francesca Pellicciotti for her considerable efforts in editing this manuscript as well as Evan Miles, David Rounce, and two anonymous reviewers whose comments significantly improved the full body of work. LSA acknowledges support from a 2011 Muire Science and Learning Center Fellowship, NSF DGE-1144083 (GRFP), and funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme under grant agreement No 759639. RSA and WHA acknowledge support of NSF EAR-1239281 (Boulder Creek CZO) and NSF EAR-1123855. WHA acknowledges support from NSF OPP-1821002 and the University of Colorado at Boulder's Earth Lab initiative. We thank Craig Anderson, Emily Longano, and Oren Leibson for invaluable field support. We thank Indrani Das, Regine Hock, Martin Truffer, Jack Holt, Eric Peterson, Brandon Tober, Dirk Scherler, Katy Barnhart, Andy Wickert, and Eric Winchell for thoughtful discussions. LSA thanks the organizers and participants of the 2010 Glaciological Summer School held in McCarthy, Alaska, which inspired this research. We thank Per Jenssen, Susan Fison, Ben Hudson, Patrick Tomco, Rommel Zulueta, the Wrangell-St. Elias Interpretive Rangers, the Wrangell Mountains Center, and Ted Scambos (NSIDC) for logistical support and the gracious loan of equipment. We thank Lucy Tyrell for facilitating outreach efforts. We also thank Joshua Scott, Wrangell-St Elias National Park and the Polar Geospatial Center for access to satellite imagery as well as Etienne Berthier for sharing DEMs. WHA thanks Waleed Abdalati, Mahsa Mousavi, and Stefan Leyk for guidance in image processing.~~

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Tables

Table 1. Parameters used for the best distributed melt and uncertainty estimates

Parameter name	Parameter symbol	Lower bound	Best	Upper bound	
Debris thickness [cm]	a	17.6	21.55	34.3	Interquartile range
	b	0.016	0.13	0.01	
	c	538	551	556	
	d	2.1	2.1	2.6	
Sub-debris melt rate [cm d^{-1}]	$\dot{b}_{ice}$	4.87	5.87	6.87	± 1 st. dev.
	h_*	8.17	8.17	8.17	
Ice cliff backwasting [cm d^{-1}]	f	4.6	7.1	9.6	± 1 st. dev.
Ice cliff slope [degree]	θ	43	48	53	± 1st. dev.

Parameter name	Parameter symbol	Min.	Best	Max.	
Debris thickness [cm]	a	17.6	21.55	34.3	Interquartile range
	b	0.016	0.13	0.01	
	c	538	551	556	
	d	2.1	2.1	2.6	
Sub-debris melt rate [cm d^{-1}]	$\dot{b}_{ice}$	4.87	5.87	6.87	± 1σ
	h_*	8.17	8.17	8.17	
Ice cliff backwasting [cm d^{-1}]	f	2.18	7.1	12.0	± 1 σ
Ice cliff slope [degree]	θ	43	48	53	± 1σ

Table 2. Statistics of debris- and melt-related in situ measurements for Kennicott Glacier

Measured variable	Mean	Std.	Minimum	Maximum
Debris thickness [cm]	13.7	13.9	0	100

Sub-debris ablation [cm d^{-1}]	4.0	1.8	0.8 (37 cm of debris)	7.3 (1 cm of debris)
Ice cliff backwasting [cm d^{-1}]	7.1	2.5	2.8	13.8

Table 3. Comparison of ice cliff backwasting rates and debris thicknesses with other glaciers

Glacier	Region	Latitude [deg.]	Mean study area elevation [m]	Range of backwasting rates [cm d^{-1}]	Mean debris thickness [cm]	Reference
Kennicott	Alaska	61	600	3-15	14	This study
Miage	Alps, Italy	46	2200	6.1-7.5	26	Reid and Brock, 2014
Koxkar	Tien Shan, China	42	3500	3-10	53	Han et al., 2010; Juen et al., 2014
Lirung	Himalaya, Nepal	28	4200	7-11	50-100	Brun et al., 2016
Changri Nup	Himalaya, Nepal	28	5400	2.2-4.5	-	Brun et al., 2018

~~Glacier~~	~~Region~~	~~Latitude [deg.]~~	~~Mean study area elevation [m]~~	~~Range of backwasting rates [cm d^{-1}]~~	~~Mean debris thickness [cm]~~	~~Reference~~
~~Kennicott~~	~~Alaska~~	~~61~~	~~600~~	~~3-15~~	~~13~~	~~This study~~
~~Miage~~	~~Alps, Italy~~	~~46~~	~~2200~~	~~6.1-7.5~~	~~26~~	~~Reid and Brock, 2014~~
~~Koxkar~~	~~Tien Shan, China~~	~~42~~	~~3500~~	~~3-10~~	~~53~~	~~Han et al., 2010; Juen et al., 2014~~
~~Lirung~~	~~Himalaya, Nepal~~	~~28~~	~~4200~~	~~7-11~~	~~50-100~~	~~Brun et al., 2016~~
~~Changri Nup~~	~~Himalaya, Nepal~~	~~28~~	~~5400~~	~~2.2-4.5~~	~~-~~	~~Brun et al., 2018~~

*Sorted by latitude

Table 4. Comparison of ice cliff coverage and melt contribution with other debris-covered glaciers

Glacier	Region	Glacier area [km^2]	Study area [km^2]	Ice cliff fractional area (%)**	Ice cliff mass loss (%)	Mean debris thickness [cm]	Study
Ngozumpa	Nepal	79.5	17.4	5	40***	0-300	Thompson et al., 2016
Lirung	Nepal	5.8	1.1	2.0	36	50-100	Buri and Pellicciotti, 2018
Kennicott	Alaska	387	24.2	11.7	26 (±8)	13	This study
Changri Nup	Nepal	2.7	1.5	7.4	24 (±5)	-	Brun et al., 2018
Langtang	Nepal	40.2	15.4	1.3	20	-	Buri and Pellicciotti, 2018
Koxkar	China	84	15.6	1.4	7.4-12	33	Han et al., 2010; Juen et al., 2014
Miage	Italy	11	3.1	1.3	7.4	26	Reid and Brock, 2014

Glacier	Region	Ice cliff fractional area (%)**	Ice cliff mass loss (%)	Mean debris thickness [cm]	Study
Ngozumpa	Himalaya, Nepal	5	40	0-300	Thompson et al., 2016
Lirung	Himalaya, Nepal	2.0	36	50-100	Buri and Pellicciotti, 2018
Changri Nup	Himalaya, Nepal	7.4	24 (±5)	-	Brun et al., 2018
Langtang	Himalaya, Nepal	1.3	20	-	Buri and Pellicciotti, 2018
Kennicott	Alaska	11.7	20 (±8)	13	This study
Koxkar	Tien Shan, China	1.4	7.4-12	53	Han et al., 2010; Juen et al., 2014
Miage	Alps, Italy	1.3	7.4	26	Reid and Brock, 2014

*Sorted by mass loss % due to ice cliffs
** % relative to each study area
***Combined contribution from ice cliffs, ponds, and streams

Figures

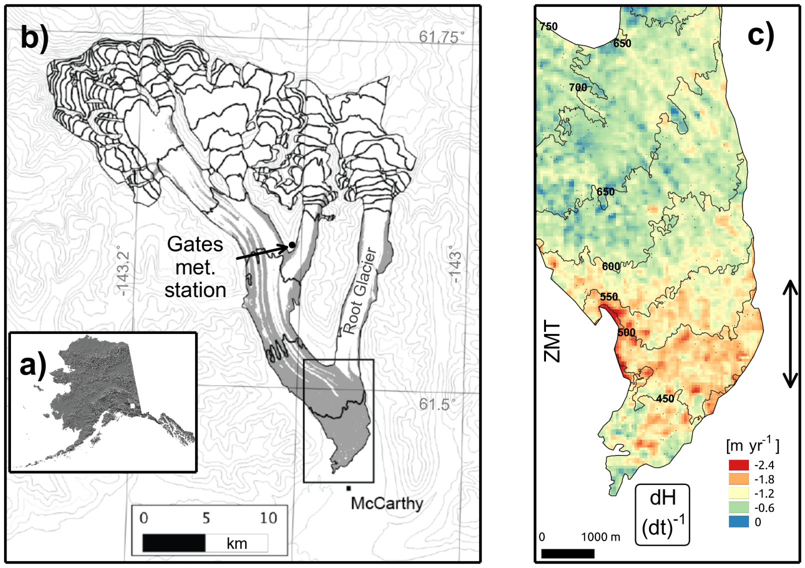


Figure 1. Map of Kennicott Glacier and the study area. a) Map of Alaska showing the location of panel b and the Wrangell Mountains. b) The Kennicott Glacier with the location of the Gates Glacier meteorological station (1240 m a.s.l.), discussed in section S1.1. May Creek meteorological station is located 15 km to the southwest of McCarthy at 490 m a.s.l.. Contour intervals are 250 m based on the ASTER GDEM V2 (2009). c) Map of the general study area with dH (dt)$^{-1}$ from 1957 to 2004 see Das et al. (2014). *ZMT* refers to the zone of maximum thinning, the extent of which is shown with the double-headed arrow. This map of the study area includes the bare-ice parts of Root and Kennicott Glaciers, where some ablation measurements were made. Elevation contours are from 2013. The units for the legend are above the labeled colors.

~~**Figure 1.** Map of Kennicott Glacier and the study area. a) Map of Alaska showing the location of panel b and the Wrangell Mountains. b) The Kennicott Glacier with the location of the Gates Glacier meteorological station (1240 m a.s.l.), discussed in the supplementary material. May Creek meteorological station is located 15 km to the southwest of McCarthy at 490 m a.s.l.. Contour intervals are 250 m based on the ASTER GDEM V2 (2009). c) Map of the general study area with dH (dt)$^{-1}$ from 1957 to 2004 see Das et al. (2014) (mean error 0.04 m yr^{-1} and 1 std 0.15 m yr^{-1} based on 3 km^2 area within 4 km of the modern terminus). *ZMT* refers to the zone of maximum thinning, the extent of which is shown with the double-headed arrow. This map of the study area includes the bare-ice parts of Root and Kennicott Glaciers, where some ablation measurements were made. Elevation contours are from 2013.~~

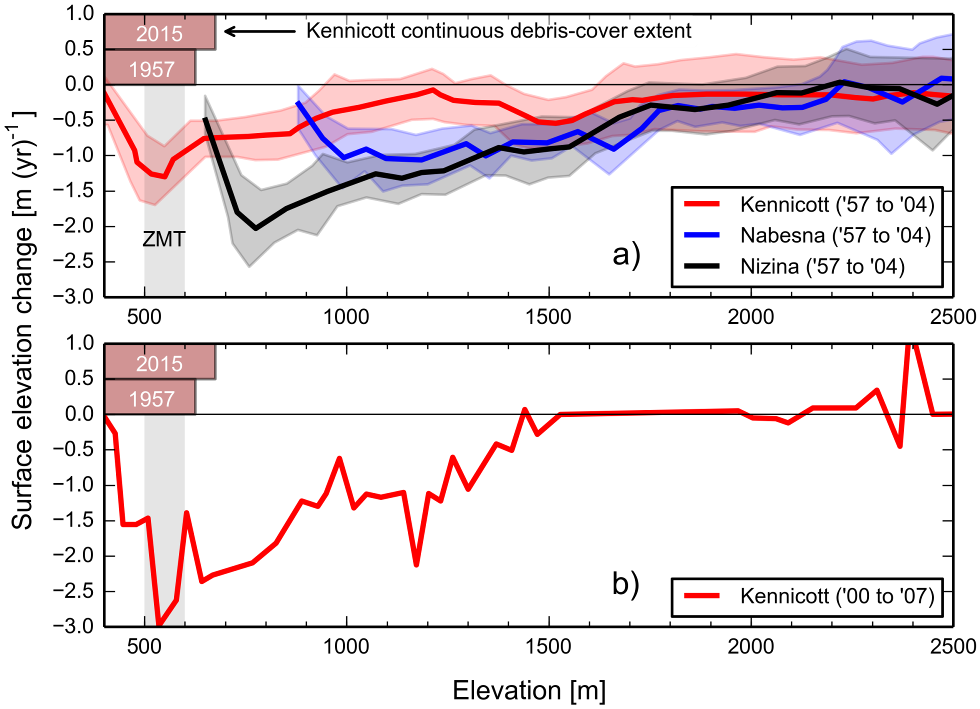


Figure 2. Surface elevation change from three glaciers in the Wrangell mountains. Surface elevation change data from Das et al. (2014). Elevations on the x-axis are derived from the 1957 digital elevation model (DEM). Take care in comparing these data to those presented in other figures which as they are referenced to the 2013 glacier surface. a) Surface elevation change derived from DEMthe differencinge between DEMs. The shaded areas reflect the standard deviation of DEM differencing (see Das et al., 2014). The Kennicott Glacier is the only glacier in the figure with a continuous debris-cover spanning its entire width. The Nabesna and Nizina glaciers have individual medial moraines at the terminus but the majority of the glaciers' termini are debris-free. The vertical grey bar is the zone of maximum thinning corrected for elevation differences. The greatest change in glacier surface elevation occurs within the portion of the glacier where debris spans the glacier width continuously between 1957 and 2015 (shown as brown bars; see Supplemental Fig. S21ure 26). The *ZMT* remains in a consistent location between 1957 and 20070 as well (Das et al., 2014). b) Surface elevation change derived from laser altimetry profiles differenced from a DEM from 2000 to 2007. See Das et al. (2014) for the laser altimetry path and a discussion of uncertainties.

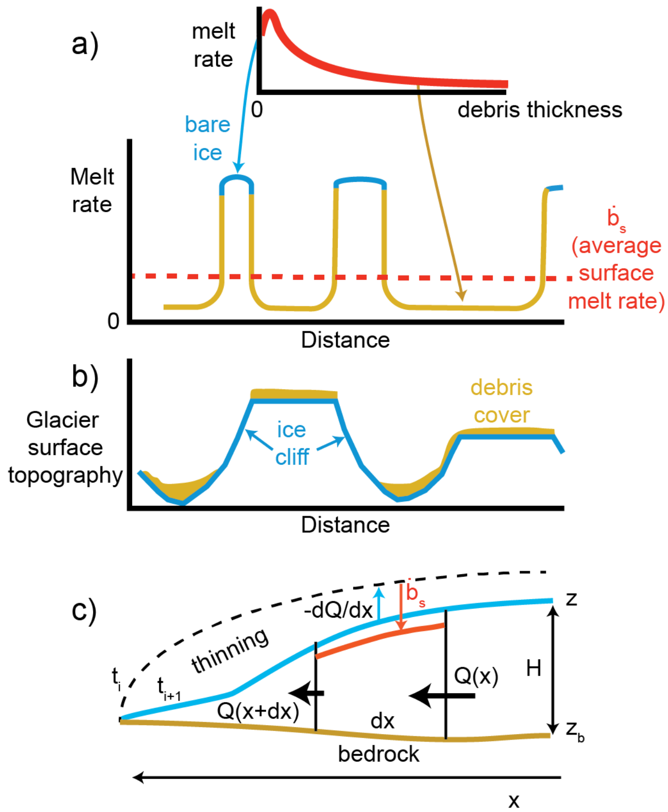


Figure 3. Schematic comparing the relative roles of ice cliff backwasting, sub-debris melt, and ~~ice surface uplift (~~ice emergence~~ rate)~~ to the lowering of an idealized glacier terminus. a) Idealized relationship between ice cliff backwasting and sub-debris melt. Not~~eing~~ that the inclination~~inclined facing~~ and low albedo of ice cliffs can lead to melt rates that exceed bare-ice melt rates on a flat surface. b) Glacier surface topography with debris cover and ice cliffs compared to melt rates in panel a. c) Schematic showing the relationship between surface melt, ice dynamics, and the thinning of the glacier through time.

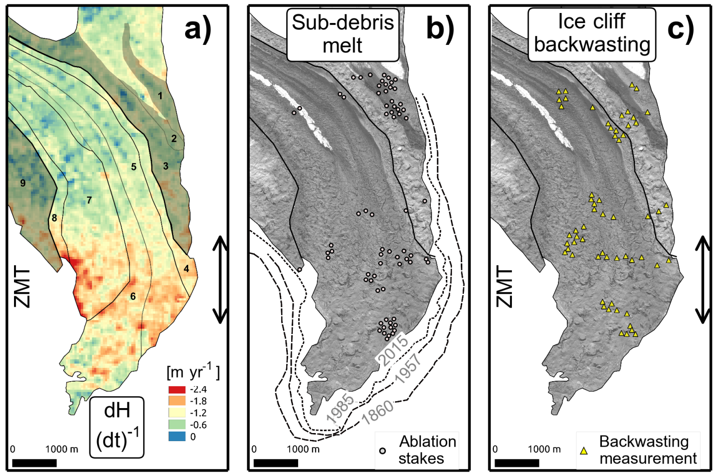


Figure 4. The study area with defined medial moraines and in situ measurement locations. This map of the study area includes the bare ice parts of Root Glacier, which are excluded and masked when making distributed melt estimates. The ~~in which we use the~~ area defined by the nine~~9~~ medial moraines in panel a is used for distributed melt estimates. a) Glacier thinning data ~~dH (dt)$^{-1}$~~ from 1957 to 2004 ~~(see~~ Das et al., ~~(~~2014). This panel uses the s~~S~~ame ~~thinning~~ data as in Fig. 1c~~C~~ but the ~~with 9 distinct~~ medial moraines are defined ~~and labeled~~. The shaded medial moraines are treated differently for distributed debris thickness estimates (see s~~S~~ection S3.1.1~~2.3~~). Note that medial moraines ~~#~~ 4 through 8 contain the majority of the zone of maximum thinning. Medial moraines ~~#~~ 3 and 9 show much thicker debris at the same elevation than the others (Fig. S14~~Supplementary Material~~). ~~The labeled and delineated moraines define the extent of the area (24.2 km^2) used for the distributed melt estimates described below.~~ The zone of maximum thinning (*ZMT*) is shown by the double-headed arrow. b) Sub-debris melt rate measurement locations. Debris was measured at all locations in panels b and c, in some cases ice cliffs and sub-debris measurements were proximal and only one debris thickness measurement was made between them. The five central medial moraines are within the two black lines, within which 69% of debris thickness measurements were made. c) Locations where ice cliff backwasting rate was measured.

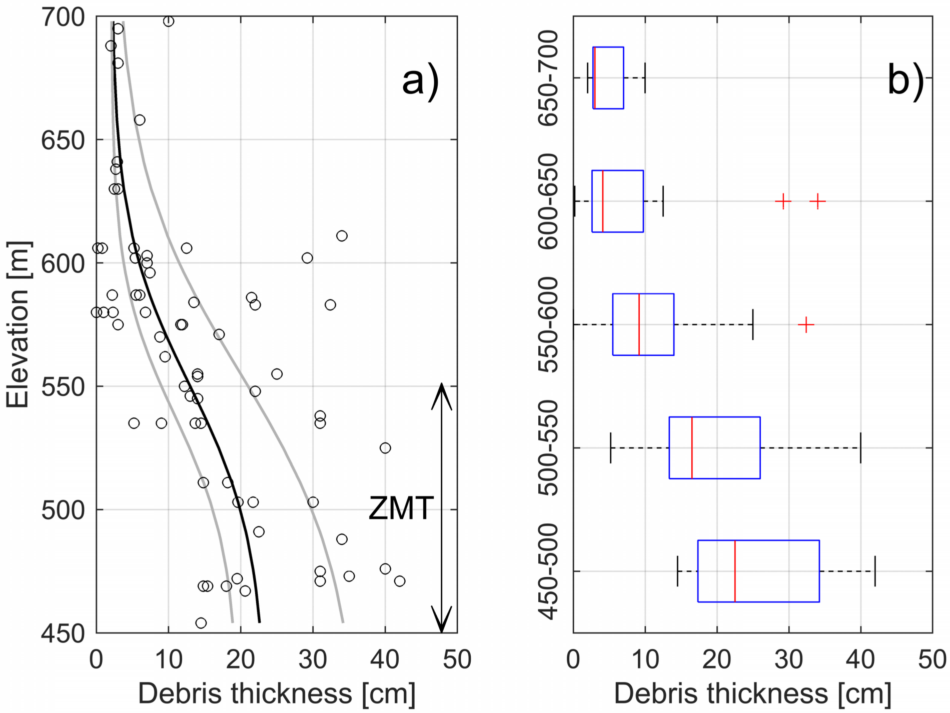


Figure 5. Debris thickness measurements for the five central medial moraines. a) Debris thickness measurements as they vary with elevation (also see Fig. S14). The points plotted are the mean--measured debris thicknesses with symmetrical uncertainties around them. ~~The mean uncertainty of the debris thickness measurements is ±0.3 cm, with a standard deviation of ±1.8 cm, and a maximum error of ±6.7 cm. Error estimates were based on repeated measurements.~~ With curve -fits through the median debris thickness (bold line) and the 25 and 75% quartiles (grey lines) from 50-m elevation bins shown in b (see Table 1 for curve fit parameters). The double-headed arrow represents the zone of maximum thinning. b) Box plots of debris thickness binned in 50-m elevation bands. The red bars are the median and the vertical blue bars are the 25 and 75% quartiles respectively. Note the sigmoidal shape of debris thickness with elevation. See the supplementary materials for curve fits applied to the other medial moraines as well as an exploration of linear curve fits through the data (Figs S14 and S18)~~estimates of debris thickness with elevation~~.

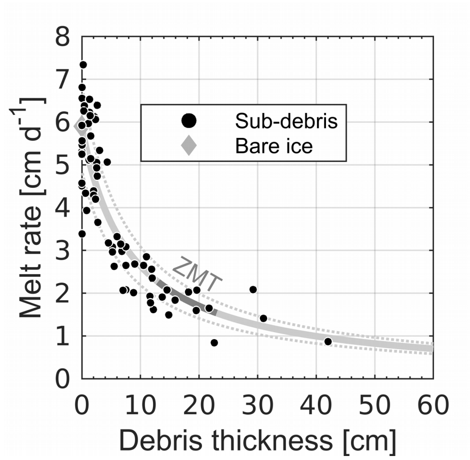
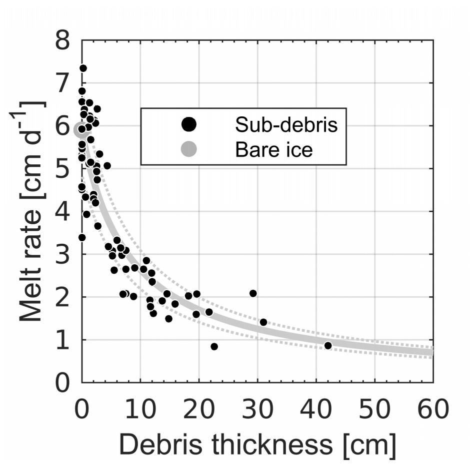


Figure 6. Sub-debris melt rate measurements. Melt rate as it varies with debris thickness. Sub-debris melt rates are corrected for the different measurement periods (see section S1.1). The solid line is the curve fit using the hyper-fit model for the best debris thickness-melt relationship (RMSE to the data is 0.8 cm d^{-1}). The portion of the best curve fit in the zone of maximum thinning (*ZMT*) is shaded darker than the rest of the line. The dotted lines represent the ±1σ error bounds used in the uncertainty estimates of distributed melt.



~~**Figure 6. Sub-debris melt rate measurements.** a) Melt rate as it varies with debris thickness. Sub-debris melt rates are corrected for the different measurement periods (Supplemental Materials). Individual melt rate measured error is smaller then the marker for each measurement, except one due to ablation pole tilt (Supplemental material). The solid line is the curve-fit using the hyper-fit model for the most likely debris thickness-melt relationship (RMSE to the data is 0.8 cm). The dotted lines represent the ±1σ error bounds used in the distributed melt estimates.~~

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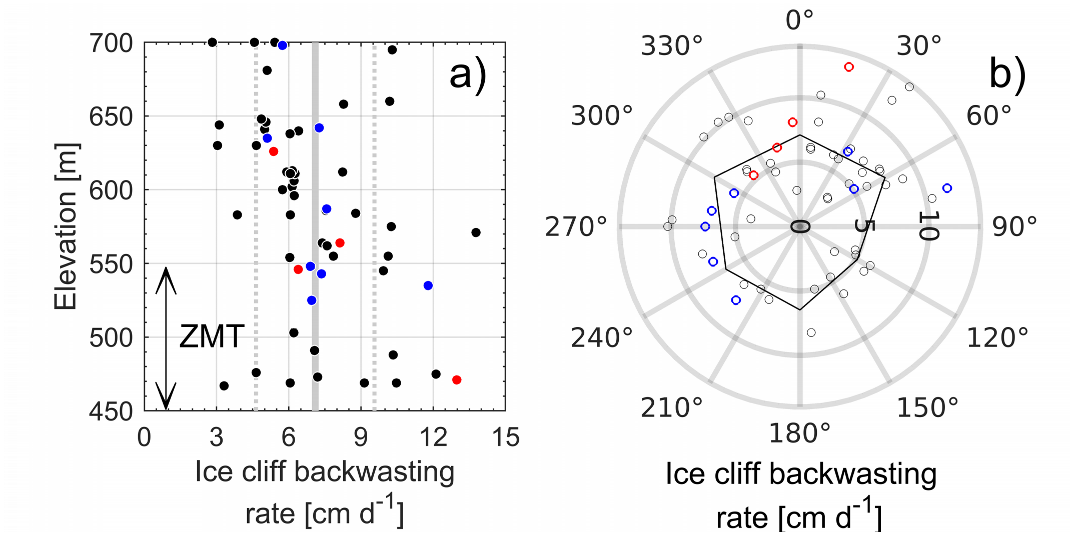


Figure 7. Ice cliff backwasting rate measurements. Ice cliff backwasting rates are corrected for the different measurement periods (section S1.2). Cliffs with streams at their base are blue. Cliffs with ponds at their base are red. a) Ice cliff backwasting rate as it varies with elevation. The solid grey line is the mean of all data 7.1 cm d^{-1}. The dashed lines are ±1σ bounds used in the distributed melt calculations (see Table 1 for curve fit parameters). The double-headed arrow represents the zone of maximum thinning (*ZMT*). b) Ice cliff backwasting rate as it varies with aspect. The corners in the solid black line represent the mean backwasting rate from 60° bins. During the field survey, ice cliffs with ponds at their base were only found facing northward (between 300º and 30º).

~~**Figure 7. Ice cliff backwasting rate measurements.** Ice cliff backwasting rates are corrected for the different measurement periods (Supplemental Materials). Cliffs with streams at their base are blue. Cliffs with ponds at their base are red. The mean error of the ice cliff backwasting rates is ±0.5 cm d^{-1}. Maximum error is ±1 cm d^{-1} for 10 cliffs that were measured over the shortest interval of all measured ice cliffs (a three week period). The standard deviation of ice cliff backwasting errors is ±0.2 cm d^{-1}. a) Ice cliff backwasting rate as it varies with elevation. The solid grey line is the mean of all data 7.1 cm d^{-1}. The dashed lines are ±1σ bounds used in the distributed melt calculations (see Table 1 for curve fit parameters). The double-headed arrow represents the zone of maximum thinning (*ZMT*). b) Ice cliff backwasting rate as it varies with aspect. The solid black markers represent the mean backwasting rate from 60º bins. During the field survey, ice cliffs with ponds at their base were only found to face between 300 and 60 degrees (northward).~~

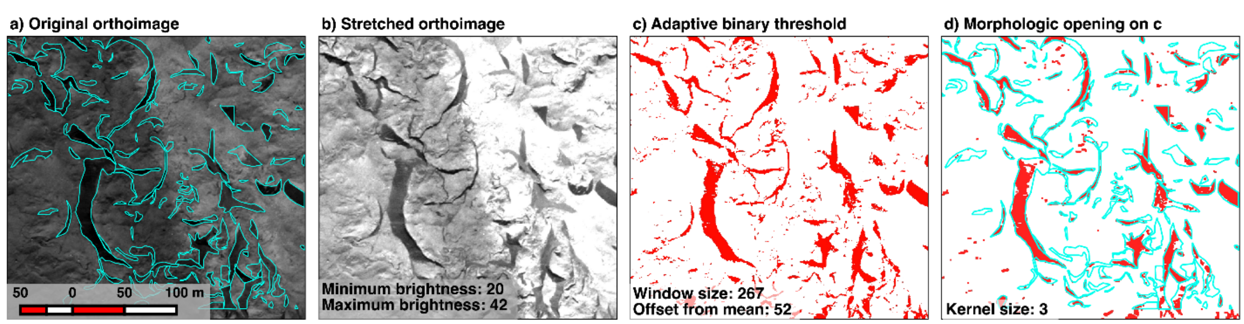


Figure 8. Ice cliff delineation workflow for the adaptive binary threshold (*ABT*) method. The extent of this area is shown by the third cyan box from the right in Figure 9. a) Original orthoimage with manually digitized ice cliffs shown in cyan. b) Orthoimage after histogram stretch using a set of well-performing brightness values from the parameter optimization. c) *ABT* on stretched orthoimage. d) Morphologic opening on adaptive binary threshold to remove small isolated false positive ice cliff delineations. Manually digitized ice cliffs used as the validation dataset are again shown in cyan.

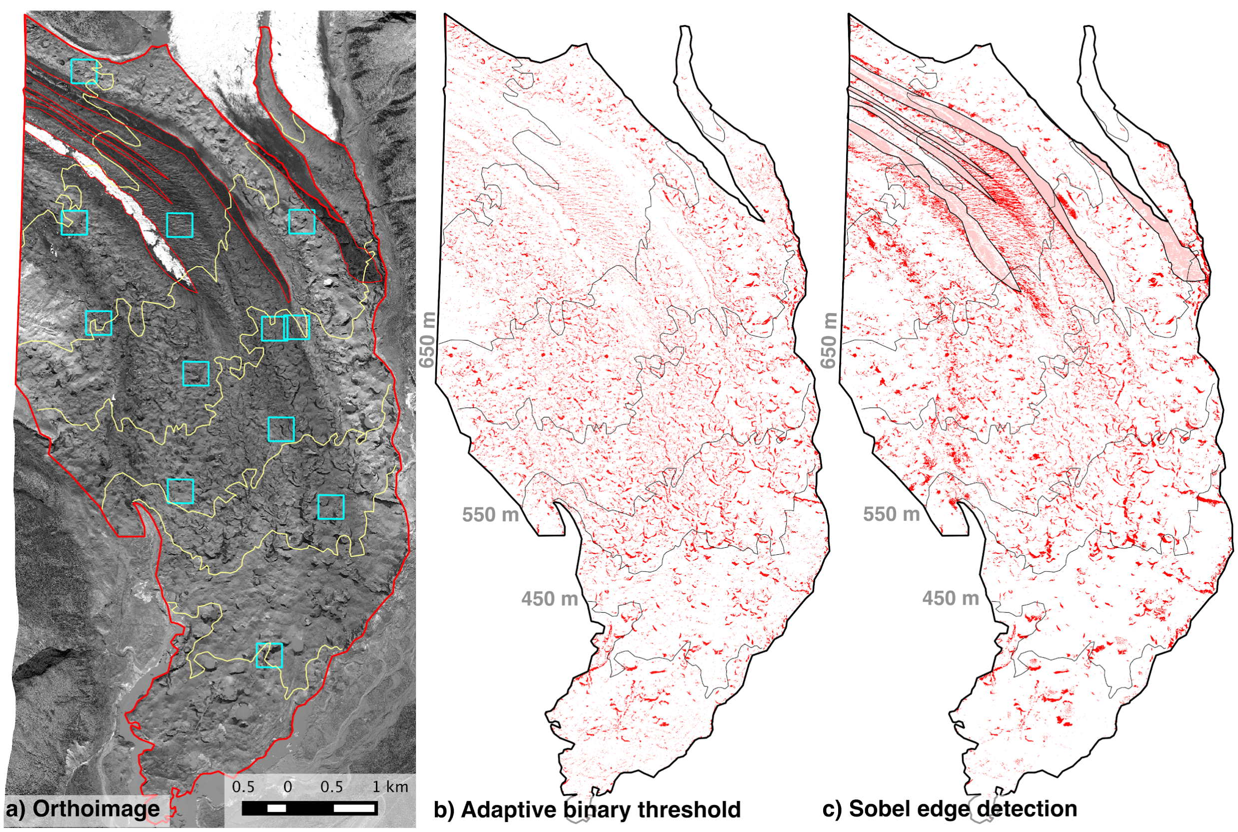


Figure 9. Results from the two ice cliff delineation methods. a) Orthoimage of the terminus of Kennicott Glacier, with the debris-covered area used for distributed melt estimates outlined by the thicker red line. The thinner red lines show regions of dark and light bare ice that required special treatment for~~in~~ the *SED* method. Thin yellow lines are elevation

contours with a 50 m contour interval from 2013. Blue boxes show the locations of manually digitized ice cliff area, used for error analysis and parameter optimization. b) Ice cliff spatial distribution as estimated by the adaptive binary threshold (*ABT*) method~~, with overlaid elevation contours from 2013~~. The outline in panels a and b show the area used for distributed melt calculations. c) Ice cliff spatial distribution as estimated by the Sobel edge delineation (*SED*) method, with overlaid elevation contours from 2013.

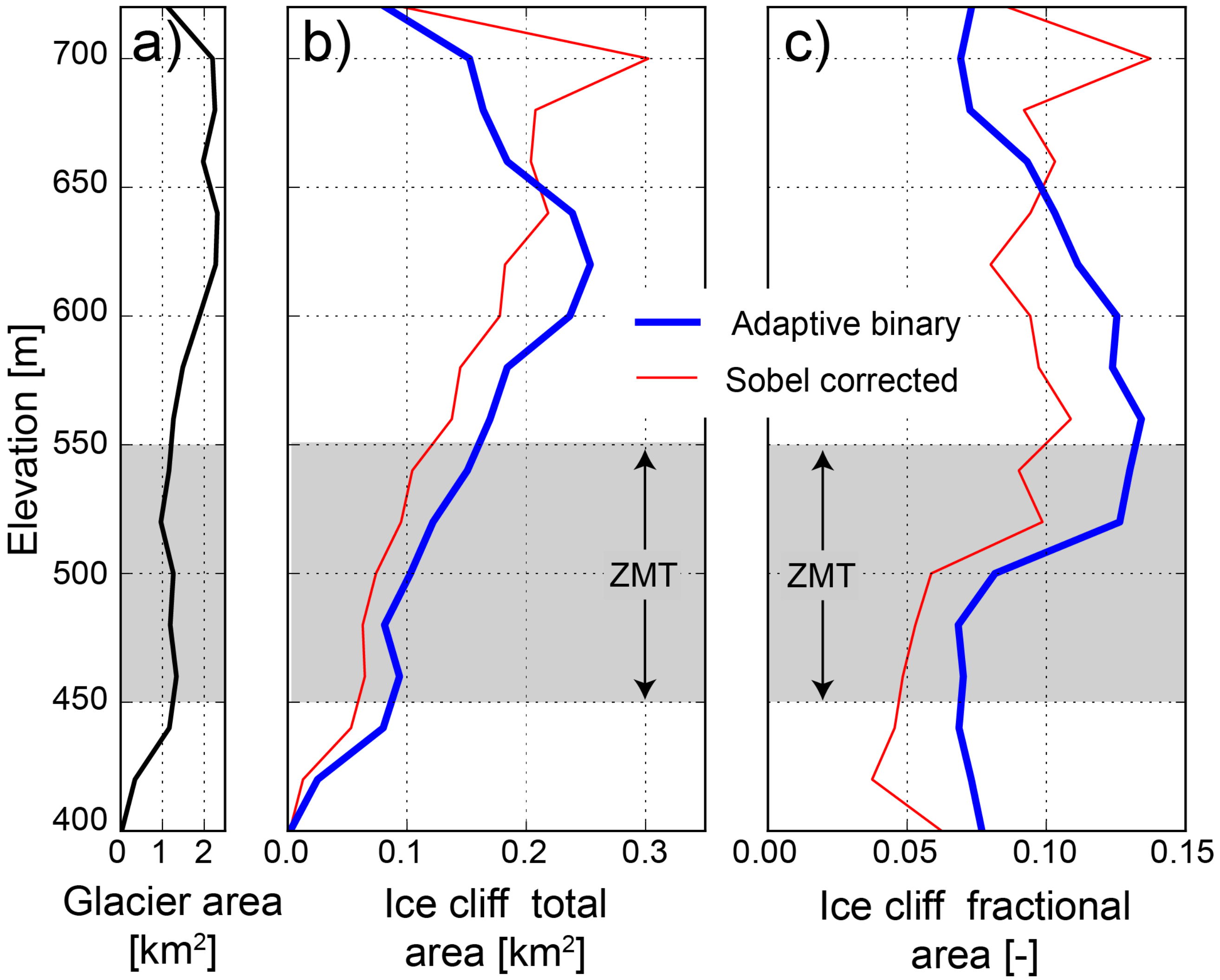


Figure 10. Results from the two ice cliff delineation methods with elevation. All panels use 20 m elevation bins. a) Glacier area as a function of elevation. b) Ice cliff area as a function of elevation. The red line shows results from the *SED* approach after false positives on dark colored ice are removed. c) Ice cliff area as a function of elevation, normalized by the glacier area within each elevation band. Note that fractional area * 100 is the percentage of ice cliff coverage.

~~**Figure 10. Results from the two ice cliff delineation methods with elevation.** a) Glacier area as a function of elevation. b) Ice cliff area as a function of elevation. The red line shows results from the *SED* approach after false positives on dark colored ice are removed. c) Ice cliff area as a function of elevation, normalized by the glacier area within each elevation band. Note that fractional area * 100 is the percentage of ice cliff coverage.~~

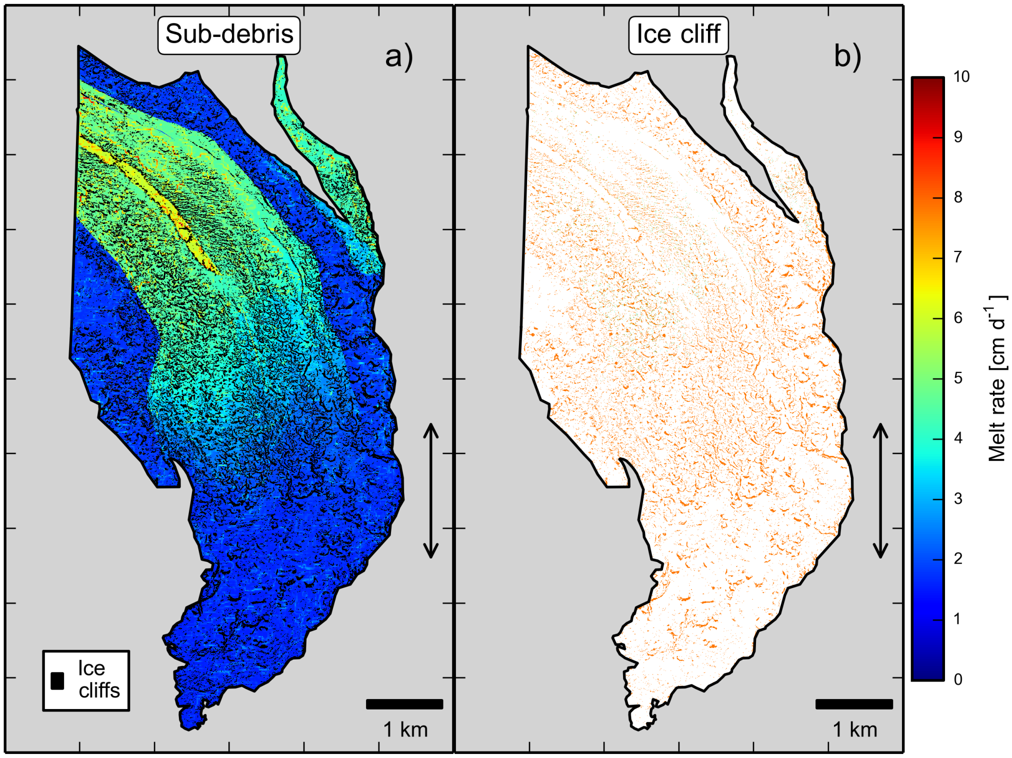


Figure 11. Distributed melt rates based on elevation and flow path (medial moraines). The zone of maximum thinning (*ZMT*) is defined by the double-headed arrows in each panel. a) Best sub-debris melt rate estimate which decreases in magnitude downglacier in the central part of the glacier. Medial moraines near the edge of Kennicott Glacier were composed of thicker debris. b) BestMost-likely ice cliff backwasting rate which we assume is uniformly distributed across the study area with a value of 7.1 cm d^{-1} (see Figs. S7 and S17 Supplementary Material for the case of backwasting rate varying linearly with elevation). Note that no clear trends were present in ice cliff backwasting rate from medial moraine to medial moraine so the same backwasting-elevation relationship is applied across the study area (Fig. S8Supplementary Figure 9).

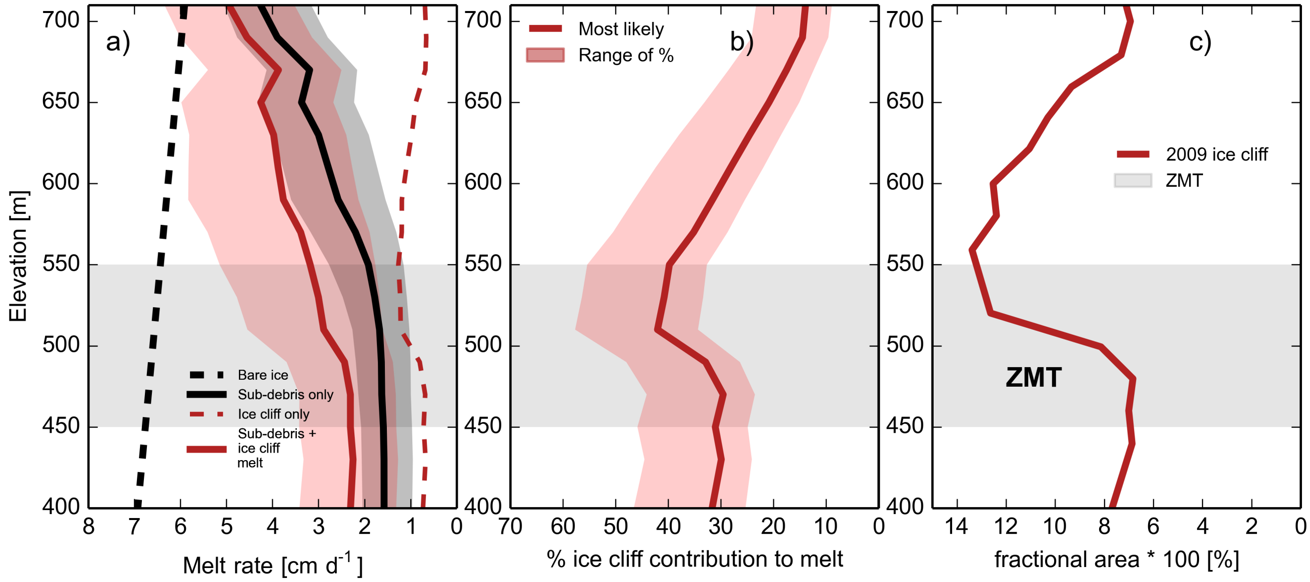
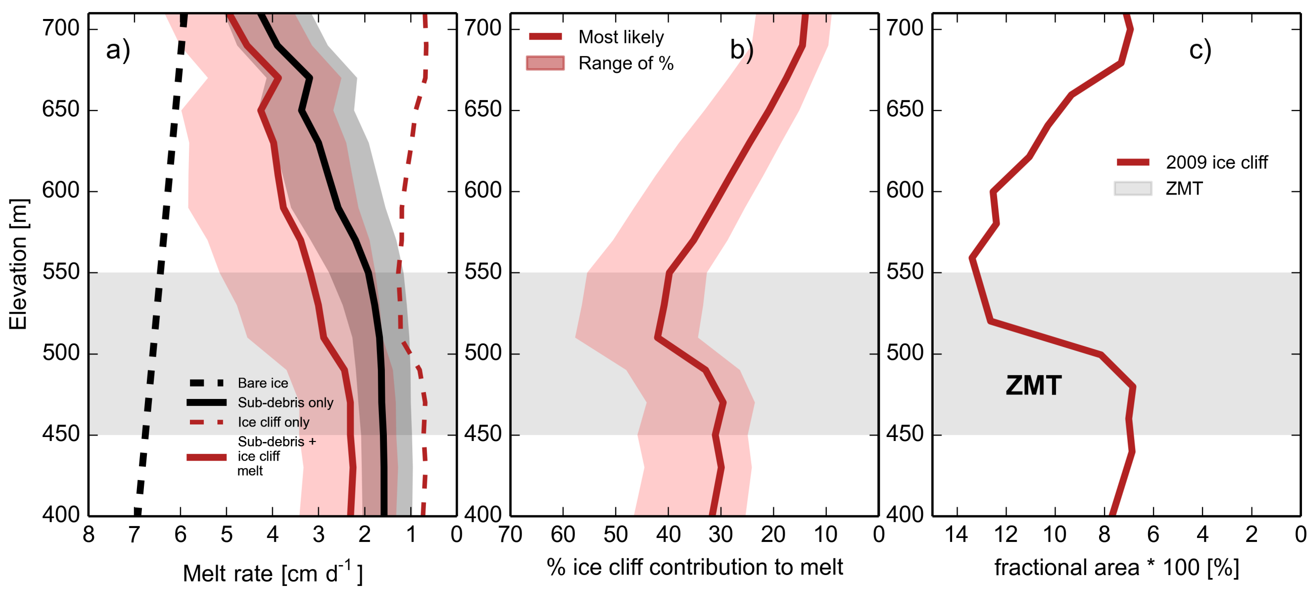


Figure 12. Distributed melt rate estimates with elevation. Elevations are relative to the 2013 glacier surface. The zone of maximum thinning (*ZMT*) is represented by the grey bands for all panels. All panels use 20 m elevation bins. a) The elevation-band-averaged (*absolute*) melt rate over the study period. The red bad contains an extreme range of sub-debris plus ice cliff melt based on compounding parameter choices such that 98.4 % of estimates lie within it (see section 2.3.1). 84.1% of estimates for sub-debris melt are within the grey shaded band. Five additional distributed melt rate scenarios are presented in section S3. Even with extreme parameter choices to increase melt rates, none of them maximize melt rates in the *ZMT*. Bare-ice estimates are based on the near-surface air temperature lapse rate from off-glacier meteorological stations and a degree-day factor for bare-ice melt (section S1.6). The decrease in sub-debris melt rate at 670 m a.s.l. is related to the increased area of medial moraine # 9 within the study area, which is covered with relatively thick debris. b) The fractional (*relative*) contribution of ice cliffs to the area-averaged melt rate (sub-debris + ice cliff) with elevation. The red band contains the extreme range of melt contributions from ice cliffs. c) The fractional area * 100 (%) coverage of ice cliffs.



~~**Figure 12. Distributed melt rate estimates with elevation.** Elevations are relative to the 2013 glacier surface. The zone of maximum thinning (*ZMT*) is represented by the grey bands for all panels. a) The elevation-band-averaged melt over the study period combining in situ measurements of ice cliff, sub-debris melt, and debris thickness. The red bad contains an extreme range of sub-debris plus ice cliff melt based on compounding parameter choices such that 98.4 % of estimates lie within it (see section 2.3.1). 84.1% of estimate for sub-debris melt are within the grey shaded band. Four additional~~

~~distributed melt rate scenarios are presented in the Supplementary Materials, and even with extreme parameter choices to increase melt rates, none of them maximize melt rates in the *ZMT*. Bare-ice estimates are based on the near-surface air temperature lapse rate from off-glacier meteorological stations and degree-day factor for bare-ice melt (Supplementary Materials). The decrease in sub-debris melt rate at 670 m a.s.l. is related to the increased area of medial moraine # 9 within the study area, which is covered with relatively thick debris. b) The fractional contribution of ice cliffs to the area-averaged melt rate (sub-debris + ice cliff) with elevation. The red band contains the extreme range of melt contributions from ice cliffs. c) The fractional area * 100% (percent) coverage of ice cliffs. Note that the fractional area of ice cliff coverage maximizes in the upper portion of the *ZMT*.~~